Using Multi-Attribute Tradespace Exploration for the Architecting and Design of Transportation Systems

by

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Abstract

The field of Engineering Systems maintains that fundamental engineering principles exist, which apply across different domains of complex socio-technical systems. In this thesis, a state-of-the art decision and design evaluation method developed using aerospace cases, Multi-Attribute Tradespace Exploration (MATE), is applied for the first time to a transportation design problem. Through the application process across domains, differences between the aerospace and transportation domain are characterized: (1) a "*mission objective*" has not emerged as a well-defined, integral concept for transportation project planning in the same way it did in the military and space communities; (2) a simple *stakeholder structure* for the purpose of the analysis is not a reasonable assumption, (3) *inheritance* (legacy structures and legacy expectations) in transportation planning brings with it the stickiness of the status quo and people's attachment to things they possess; (4) *several cost types* exist in addition to monetary costs, e.g. harmful effects to life and spending of scarce resources (time, money); (5) *decisions about the welfare of stakeholders* in transportation planning are inextricably linked to technical decisions. It follows that fundamental engineering systems design principles need to be general enough to encompass these domain differences.

Decisions about the welfare of stakeholders (public, future generations, environment) by a legitimized representative decision maker raise the question about the desirability of prescriptive guiding principles for decision making, in order to ensure consideration for the represented constituency when their interests need to be traded off with personal and organizational interests of the decision maker. Decision makers themselves seek such guidance to help them in trading off and justifying decisions about multiple competing goals in complex situations. One established method to provide such guidance is Cost-Benefit Analysis (CBA). CBA is a central, established, prescriptive evaluation method used in several domains, including transportation.

In order to compare insights gained through the emerging method MATE and the established method CBA, two case studies, a Chicago Airport Express and a High-Speed Rail link between Portugal and Spain, are evaluated using those two methods. CBA assumes a broad view over all affected stakeholders, decision making or not, and seeks to ensure that net benefits to society

outweigh net costs. MATE seeks to best meet decision makers' expectations for a system. Attributes (tangible and intangible) that are valuable to individual stakeholders, but not to society as a whole, are captured in the value-based approach in MATE. They are purposefully excluded in CBA. A challenge that the value-based approach in MATE brings about are framing issues that can arise when utility theory is applied to decision making stakeholders who have mandates to represent other stakeholders.

For both aerospace and transportation domains, political vision and technical understanding of properties of different designs are important for decision making. A real feedback cycle between goal capture and low-fidelity technical modeling of different design options as suggested in MATE does not seem to exist in transportation planning. MATE seems useful as a tool to support improved communication about system expectations and technical options. Future research will need to address how value-based attribute capture can be performed in the typical complex stakeholder structure of transportation systems. Recognizing that problems of equity and value judgments are an inherent part of (some) technical decisions, the question of how to support a decision maker in expressing those attributes (even if difficult and controversial) and understanding different design concepts' impact on technical properties becomes part of the design engineer's job.

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Chapter 1 Introduction

Since the beginning of life, creatures have traveled. Human and animal-powered transportation allowed the first humans to populate the world, gather materials to construct settlements and build useful items for everyday use. Much later in human history, with the development of ships and land vehicles, greater quantities could be transported faster and further, allowing the crossing of large bodies of land and water and the further exploration of unknown places in the world, as well as the establishment of international trade routes. The Industrial Revolution opened up a new chapter in the history of public transportation with the advent of steam-powered rail transportation. The substantial investment in track infrastructure on land enabled mass transportation at a lower cost per trip, increasing the capacity for people and goods transportation along key corridors. In the 20th century, the automobile and finally commercial aviation enabled people to move over long distances and reach almost every point on earth within a day. The level of mobility that is possible today changed land-use patterns, housing, and business location choices on a national and global scale. Transportation is more than a technical capability; mobility is, and has been over history, a source of power and prestige both for individuals and governments. Today, the movement of people and cargo via air, road, rail, waterway or pipeline enable virtually every economic activity in a globalized world and is the basis of the efficiency of industrial production. Time and location are key features of modern industrial production of goods and services. With the development of new transportation modes and the steady additions to existing transportation infrastructure, systems have become larger and more complex. Engineering Systems is an extension of traditional engineering disciplines that specifically tackles the issues that emerge through the larger and more complex nature of modern large-scale technical systems by promoting a comprehensive view and the use of an interdisciplinary tool set to solve problems. Engineering Systems, as understood by MIT's Engineering Systems Division (ESD), is the study of a class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society (MIT Engineering Systems Division 2009).

The first chapter introduces Engineering Systems, and specifically Transportation Systems as one special class. The field of Engineering Systems maintains that fundamental engineering principles apply across complex socio-technical systems of different domains. If a method originating in one domain proves useful for application in another, the observation hints at common engineering systems principles that the method in question addresses. Study and application of such a method across domains will help to identify such design principles. On the other hand, factors that prohibit application of a method across domains point out domain differences. Explicit knowledge of domain differences is essential in the quest for developing domain-independent engineering systems methods. It is for this reason that a state-of-the-art decision and design method developed using aerospace cases is applied to the architecting and design of transportation systems in this thesis. In addition to information about context, motivation and contributions, Chapter 1 introduces the research questions that are addressed and outlines the structure of the thesis.

1.1 Context

1.1.1 Systems Engineering and Engineering Systems

Large-scale technical systems consist of a large number of interacting components whose behavior is often hard to model and predict accurately. Example systems like satellite, logistics, or electricity distribution systems exhibit complex socio-technical interactions and need to cater to different, often conflicting stakeholder interests. With the growing complexity of systems, more sophisticated systems engineering approaches are needed.

Evolving beyond its earliest applications in the Bell Telephone Laboratories, NASA, and the US Department of Defense (Schlager 1956; Hall 1962), systems engineering today is an interdisciplinary field of practice and research that is applied within different engineering domains. Originating in the aerospace and telecommunication domains, the term systems engineering denotes "an interdisciplinary approach and means to enable the realization of successful systems" (INCOSE 2004).

The discipline of *engineering systems* builds on systems engineering. Engineering Systems, as understood by MIT's Engineering Systems Division (ESD), is the study of a class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society (MIT Engineering Systems Division 2009). While engineering systems holds on to the generation and evaluation of the technical elements of system designs, it expands its focus to consider contextual factors such as political, socioeconomical, managerial, and environmental factors as important elements for realizing successful systems that do not have purely technical solutions (Rhodes and Hastings 2004). Established in 1998, the Engineering Systems Division (ESD) at MIT focuses on the advancement of Engineering Systems research across multiple domains, including aerospace, transportation, logistics, and energy.

1.1.2 Transportation Systems

This thesis is concerned with the architecting of transportation systems as one class of engineering systems. A transportation project, as understood in this thesis, is a project that encompasses the conceptual design, engineering and construction of transportation infrastructure, and its subsequent operation. In many places in developed countries today the times are changing from eras of expansion to those of predominantly maintenance and operation of existing transportation infrastructure (Meyer and Miller 2001). However, in a number of areas, such as high-speed rail or integration between different modes of transportation (e.g., airport connectors), construction activity is still taking place. The transport field can be looked at from different perspectives. A common decomposition is in terms of infrastructure, vehicles, and operations. *Infrastructure* consists of the fixed installations of transportation activity, including rights-of-way, terminals, power and communication transmitting devices, and facilities for parking and maintenance. *Vehicles* are the physical objects that travel along appropriate rights-of-way and contain the physical payload (people or goods). *Operations* refer to the non-tangible structures and functions that are needed to construct and run transportation systems. Operations include the procedures for operating and maintaining infrastructure and vehicles, as well as the supporting financial, legal and political procedures.

Today, transportation systems are closely linked to their surrounding environment. Zoning, geography and the economic situation of a region determine the need for and feasibility of transportation facilities. As much as transportation systems are vital, so too do they leave their negative footprints on a region: noise, pollution, ecological degradation, safety risks, and loss of open spaces are some of the adverse effects, which, to varying degrees, people living in the vicinity of transportation activity must bear. Examples like the controversial Big Dig in Boston or the lengthy discussion about the expansion of airports across the world (for example, Boston Logan International Airport) exemplify that the addition of transportation infrastructure may come at substantial inconvenience for individuals, and that those individuals are often willing to stand up against it. The growing interconnectedness of transportation systems to other technical and societal systems, such as energy generation or business agglomeration in an area, will propagate change to those connected systems. Despite the toll that transportation takes on people's space and environment, mobility is a necessary requirement for individual happiness and economic growth worldwide. Enabling mobility is an important service, or "good", for national governments to provide to the public, and most governments incur significant expenses every year to maintain transportation infrastructure, funded frequently from tax revenues. New infrastructure comes at significant expense (Big Dig: $22B (Associated Builders and Contractors Inc.)[1]) and is often funded at least partially through public debt. Sometimes new infrastructure projects are at the limit of political realizability. Due to the high price tags and long lifecycles of civil structures- in the range of several decades- transportation planning has to assume a long-term perspective on positive and negative impacts of a system (for example on land-use, the urban and regional landscape, and the environmental and economic situation of a region), bearing in mind the changing environment in which the system will operate.

1.2 Contribution

While unique in terms of domain, engineering systems exhibit a number of common characteristics that suggest the possibility that fundamental engineering system principles exist and can be applied across domains. In this thesis a state-of-the art decision and design evaluation method developed using aerospace cases, Multi-Attribute Tradespace Exploration (MATE), is applied for the first time to a transportation design problem. Through the application process, differences between the space and transportation domain are characterized. Two case studies illustrate the complementary insights that are gained from a central evaluation method in transportation planning, Cost-Benefit Analysis, and an emerging method, MATE. The first case study demonstrates a MATE study and Cost-Benefit Analysis applied to a Chicago Airport Express, and discusses and compares results. The second case study demonstrates the set-up of a MATE analysis (but not the results) applied to High-Speed Rail freight line linking Lisbon to Madrid, a more complicated transportation design problem.

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[1]Retrieved 12/27/2009, from http://www.abc.org/Newsroom2/News_Letters/2008_Archives/Issue_29/Union_Only_Big_Dig_Price_Tag_Balloons_to_22_Billion.aspx

1.3 Motivation

MATE is a decision making and design evaluation approach for structuring and analyzing conceptual designs, originally developed using aerospace applications. MATE responds to a number of criticisms regarding current space systems design methods:

- A priori design selection without analysis or consideration of other options;
- Inadequate technical feasibility studies in the early stages of design;
- Insufficient regard for the preferences of key decision makers;
- Disconnects between perceived and actual decision maker preferences;
- Pursuit of a detailed design without understanding the effects on the larger system; and
- Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest.

(Diller 2002)

In the above citation and in this thesis, "design" always refers to decisions about high-level, conceptual design parameters and not a detailed characterization of the system. "Design" and "design concept" are used interchangeably in this thesis, since the focus is on the conceptual design phase. MATE offers the ability to generate, and assess at a high level, a large number of design concepts early in the design process. The systematic variation of design concepts over a number of variables makes it possible to explore the sensitivity of system performance to a changing environment (uncertainty) or user needs (value change). MATE is a value-based decision and design method, meaning that stakeholders' perceived values, and not arbitrary performance metrics, are used as decision metrics. A more detailed description of the MATE process is provided in Chapter 2.

MATE is ultimately intended to be useful across different domains of engineering systems. Four reasons motivate the extension of MATE to applications in the transportation domain.

1) Transportation systems and space systems exhibit a number of similar characteristics (e.g., high price tags, long development time, and unique designs). Good and bad choices early on in the process of conceptual design are locked in and have long-lasting consequences, making conceptual design critical for both domains. MATE specifically supports decision making in this early phase of design by broadening the information basis for the crucial decision about an architecture concept. Long-lived systems are likely

to operate in different uncertain contexts and environments, which brings with it the need for value-robust design. Value robustness is defined as the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs. Dynamic MATE extends Static MATE to address design for value-robustness over time. The difference between Static and Dynamic MATE is discussed in section 2.1.3. Establishing the applicability of Static MATE to transportation design problems is a necessary prerequisite for potentially applying Dynamic MATE to transportation problems, which would offer additional sophisticated tools for exploring a most important area of concern for transportation planning.

2) Possible domain-inherent biases in MATE can be revealed through testing its applicability within a new domain. If commonalities are found, they hint at domain-independent properties.

3) Both domains exhibit several stakeholders with conflicting interests, who are engaged in a lengthy and highly political planning process. Addressing this issue in the aerospace domain, MATE calls for a feedback cycle between decision makers and designers, during which properties of design options and requirements are reviewed. The MATE process is intended to encompass several iterative interviews to elicit and validate user expectations on the system, acceptable performance ranges, acceptable value trade-offs and discussion of results and possible design trade-offs. The planning and construction process of transportation facilities is a highly complex coordination problem, and a systematic approach taking into account different viewpoints is strongly needed. The MATE process provides opportunities for learning about the trade-offs between properties of a large number of designs by key decision makers. By providing additional information in each iterative step, it may help multiple decision makers with differing interests achieve an acceptable consensus faster in negotiations.

4) Additional new insights for transportation design and decision making may be gained through the following benefits of MATE:

   - Support in the generation (not only evaluation) of design concepts, and

- Visualization and communication of complex system tradeoffs in both technical (design) and preference (value) metrics.

For the purposes of this these, the following describes the definitional boundaries of generic space and transportation systems. Space systems consist of all of the devices and organizations that form a mission-oriented space network, including spacecraft, mission payloads, ground stations, data links among spacecraft, mission or user terminals, launch systems; and directly related supporting infrastructure (The free online dictionary 2008). Transportation systems consist of physical objects, typically vehicles, the network infrastructure, and operation schedules, as outlined earlier in this chapter. Depending on the specific design problem, the system boundaries will be defined more narrowly as appropriate for the problem.

1.4 Research questions

Four questions guided the research in this thesis to assess the applicability of MATE within the transportation domain. A prerequisite to the exploratory application to a case study was to understand the domain context in which transportation planning takes place, and how it differs systematically from the space domain. The individual research questions are listed below:

1. What design methods are used for transportation systems planning? What are their limitations? What alternative system analysis methods are available?

2. What implementation issues arise if MATE, as a systems analysis method developed within the aerospace domain, is applied to the transportation domain?

3. What methodological insights emerge through the application of Cost-Benefit Analysis and MATE, individually and complementarily?

4. What insights are gained from the application of MATE to two transportation case studies for both MATE and transportation planning?

Questions 1 and 2 are addressed through literature research (Chapter 2), discussion of high-level applicability of MATE to transportation problems at a conceptual level (Chapter 3), and experiences made with the actual work of applying MATE to two transportation case studies (Chapters 4 and 5). Question 3 evaluates the information that decision makers gain from MATE as a new method, and a widely adopted method for transportation project evaluation, Cost-

Benefit Analysis, respectively (Chapters 4 and 5). The literature review motivates the choice of Cost-Benefit Analysis as point of comparison for MATE and discusses the scope of both methods. Question 4 captures lessons learned from both case studies for MATE and transportation planning.

The following section introduces the two case studies of this thesis.

1.5 Introduction of cases

Insights about the applicability of MATE to the transportation domain emerged in large part through work on two transportation case studies to which the author sought to apply MATE. The case study discussed in Chapter 4 treats the conception of an airport express for the City of Chicago. Data was collected during an internship that the author performed at the Chicago Transit Authority in the summer of 2008. The project is a "wish project" in that it has been discussed for several years and the need for better airport accessibility has long been recognized. There are, however, no concrete plans to implement the project soon, and plans tend to be tabled when more urgent issues require attention, such as the economic downturn starting in the summer of 2008.

The second case study deals with the design of a High-Speed Rail line between Lisbon, Portugal and Madrid, Spain.[2] The project is more complex than the first Chicago Airport Express for several reasons, including its international scope with impacts on funding, stakeholder structure and coordination, the consideration of using High-Speed Rail technology for freight transport, when it has never been done before, and the consideration of mixed passenger and freight operations. The second case study consists of the set-up of a MATE study, its comparison to a Cost-Benefit Analysis for the project, and a discussion about parametric modeling of underlying relationships for this specific problem. Due to the scope of the thesis the parametric modeling is not complete, nor is a tradespace generated as it requires the completion of the parametric model. Additionally, the needed information and insight into causal relationships are discussed for those relationships for which no parametric models could be developed. In addition, Chapter 5

[2] PhD student Ms. Diana da Silva Leal from the University of Coimbra in Portugal visited MIT as an MIT-Portugal Program visiting scholar in the spring of 2009 and worked together with the author under the supervision of Dr. Adam Ross and Dr. Donna Rhodes on the application of MATE to the High-Speed Rail design project.

discusses institutional differences between Portugal and the US. These differences illustrate the institutional responses in two countries to the challenge of explicitly considering both political expectations and technical properties of transportation design concepts. When applying MATE to the design of systems outside of the US, different institutional structures and decision making processes need to be considered.

1.6 Thesis Outline

Chapter 1 provides an introduction to engineering systems and transportation systems and motivates the exploratory research in this thesis. Chapter 2 reviews literature about the transportation planning process and two methods of interest, Cost-Benefit Analysis (CBA) and Multi-Attribute Tradespace Exploration (MATE). Shortcomings of CBA as an established method are discussed and its comparison to MATE as an emerging method is motivated. In preparation for the case studies, Chapter 3 discusses the application of the set-up of a MATE study to problems in the transportation domain at a conceptual level and highlights domain differences. The applicability and usefulness of MATE for the transportation domain is assessed by applying it to a case study in Chapter 4, using an Airport Express for the City of Chicago as a case example. This case study represents the first application of MATE to a problem in the transportation domain. The information that is gathered and combined in the decision making processes of two methods is compared: the widely used and established method CBA, and the new method MATE. The case study shows that both methods provide complementary insights and may be used together for a more complete evaluation. Chapter 5 presents the second case study, Portuguese High-Speed Rail, and discusses the set-up of MATE to a more complex transportation design problem. Chapter 6 summarizes the results of the cases and discusses insights from this thesis, discusses areas for future research, and provides concluding remarks.

Chapter 2 Literature Review

This chapter concentrates on the practice of transportation planning in the US and methods used, CBA as a key decision making method in transportation, and a description of the MATE process and past applications.

2.1 Multi-Attribute Tradespace Exploration (MATE)

MATE combines two techniques used in technical design and decision making: Multi-Attribute Utility Theory (Keeney and Raiffa 1993) and Tradespace Exploration (Ross, Hastings et al. 2002). Both elements are explained in the following sections.

2.1.1 Multi-Attribute Utility Theory

MATE incorporates Multi-Attribute Utility Analysis (MAUA) to capture user requirements. MAUA is based on Multi-Attribute Utility Theory (MAUT), both of which were developed by Keeney and Raiffa (1976) and are sometimes used as interchangeable terms. The difference is that MAUT is the theoretical construction of the multi-attribute utility function, while MAUA is the process of elicitation and evaluating alternatives on that basis. MAUT makes possible the calculation of the overall utility of multiple attributes and utility functions. Attributes are features of a product or system that the user takes into consideration when deciding between any two design options. Single-attribute utility is a dimensionless metric representing the satisfaction derived from having a certain level of a single attribute X. Multi-attribute utility is the joint utility level derived from having specific levels X_1 of multiple attributes X^i , which accurately reflects a decision maker's preferences can be difficult. Utility is measured on an ordered metric scale (ordinal scale) ranging from 0 to 1 and is useful for ranking purposes between at least two different utility values X_1 and X_2. According to (de Neufville 1990), a "Value" function has only ranking information, but "Utility" is a special type of value function that also has strength of preference information, so it is more than just ranking information. A utility of 0 and a utility of 1 have meaning to the particular decision maker, for example "minimally" and "fully" satisfied. A positive linear transformation of a single-attribute utility function does not change the resulting preference ordering. Single-attribute utility functions can be used to express the relative desirability of having a specific value X_i of an attribute $X^i{}_i$.

In equations, the single-attribute utility derived from value X_i (level of attribute X_i) is U_i=$U_i(X_i)$.

To compare designs that have more than one attribute of interest (n attributes), single-attribute utility functions U_i need to be combined into a multi-attribute utility function U. Simple forms of multi-attribute utility functions include the following:[3]

Weighted sum: $U(X)=\sum_{i=1}^{n} k_i U_i(X)$

Multiplicative function: $U(X)=\prod_{i=1}^{n} U_i(X)$

Inversed multiplicative function: $1-U(X)=\prod_{i=1}^{n} (1-U_i(X))$

Keeney and Raiffa (1976) propose a generalized form of multi-attribute utility functions, the Keeney-Raiffa function:

$KU(X)= \prod_{i=1}^{n} (Kk_iU_i(X)+ 1)$ for $K\neq0$, and

$U(X)= \sum_{i=1}^{n} k_i U_i (X)$ for $K=1$

K is a normalization constant and the solution to $K+1= [Kk_i +1]$, and the single attribute utility functions $U_i(X_i)$ and k_i "weights" are elicited from the decision maker whose preferences are being captured in the multi-attribute utility function U(X).

The constant k_i is technically a "swing weight" that incorporates the "cross terms" in the multiplicative functional form, meaning that it takes into account the bundle of other attributes as well as the particular "ith" one. The value for k_i can be retrieved by eliciting the utility of a design that has all attributes set to the least desirable values and the attribute in question to its maximum desirable value X_{iMax}.

While MATE typically uses MAUT to aggregate attributes into selection criterion score, this is not required. Any aggregation method can be used that reduces different attributes (selection

[3] For reference: $U_i(X)$ is the single-attribute utility, U(x) is the multi-attribute utility, X_i is a single-attribute level, X is an attribute vector, k_i is a single-attribute weight constant, K is a normalization constant, n is the number of attributes

criteria) to a single metric. Ross (2003) justifies the choice of MAUT in MATE to capture user preferences in the following way.

> It [MAUA] provides for a systematic technique for assessing customer "value", in the form of preference for attributes. Additionally, it captures risk preferences for the customer. It also has a mathematical representation that better captures the complex trade-offs and interactions among the various attributes. In particular, the strength of Multi-Attribute Utility Analysis lies in its ability to capture a decision maker's preferences for simultaneous objectives.
>
> (Ross 2003)

The terms *user* and *customer* have been used somewhat interchangeably in this current thesis so far when talking about requirements capture. Both stakeholder groups, users and customers, have preferences about different attributes of a system and therefore come to mind when talking about requirements capture. Users and customers are however two different stakeholder groups and generally need to be treated separately.

Single-attribute utility functions can be obtained in several ways. Relatively quick ways are sketching, or derivation by analogy from a known utility function. A more rigorous, but also more time-consuming, way is to elicit single-attribute utility functions in a structured utility interview with stakeholders. In order to satisfy the axioms of Multi-Attribute Utility Theory (Keeney and Raiffa 1993), the analyst must ensure that the attribute set is defined by the decision-maker; including precise definitions for each attribute with units, an acceptable range $[X_{iMin}, X_{iMax}]$, and a monotonic preference for the direction of increasing goodness.
$U_i(X) = 0$ is set at the value X_{iMin} of an attribute that is the least desirable, but still acceptable. $X_i > X_{iMin} = U_i^{-1}(0)$ is a hard requirement, since designs that do not at least deliver level X_{iMin} of an attribute are rejected based on that attribute alone. $U_i(X_i) = 1$ is set at the most desirable value X_{iMax} of an attribute.

Richards (2009) comments on sources for additional guidance on value elicitation in MATE:

> The issue of stakeholder value elicitation is core to the MATE process and well-documented in existing literature. Ross (2003) provides a detailed explanation of the multi-attribute utility function and a description of recommended techniques for eliciting the single-attribute and multi-attribute utility functions (*i.e.*, lottery equivalent probability method and corner point interviews, respectively). To examine the trade-off between rigor and ease of implementation, (Spaulding

2003) discusses the implications of simplifying the elicitation of single-attribute utility functions using hand-drawn utility curves and linear, risk-averse preference relationships.

(Richards 2009)

MAUA was developed for a single decision maker. Regarding the question of how to treat multiple decision-makers in MAUA, Ross (2003) writes:

> A recurring problem in utilizing decision analysis methods is the issue of multiple decision makers. Both (de Neufville 1990) and (Keeney and Raiffa 1993) mention the difficulty of assessing the utility of multiple decision makers. Since the utility function scales are not ratio scales, there is no absolute zero value, and hence, no way to compare values across functions. Only by making value assumptions (such as one person's preferences being subordinate to another's), can a single aggregate utility metric be defined. Keeney and Raiffa (1976) recommends using a "supra- decision maker" model where one person creates a multi-attribute utility function whose single attribute utility functions are the multi-attribute utility functions of each decision maker. The weights for each decision maker are then subjectively determined by the supra-decision maker. Economist Kenneth Arrow won the Nobel prize partly for showing that no aggregation method exists without making someone dictator, or in other words, there does not exist a consistent, equitable method for social choice (Arrow 1963). Scott and Antonosson (2000) however, proposes that Arrow's Theorem may not apply to engineering design since it is not a "social choice problem". Comparisons of strength of preference, coupled with questioning the necessity of equity for engineering design, may allow for the creation of aggregate decision maker functions for design. Additionally, not explicitly aggregating the decision makers would avoid Arrow's Impossibility theorem for the designers, and instead put off the intransitivity of the group preference for the decision makers to resolve in negotiation. In this way, the designers would avoid biasing the decision tools and instead highlight important tensions in the preferences.
>
> (Ross 2003)

The literature research on characteristics of the transportation domain in section 2.2 will demonstrate that technical decisions in the transportation domain are inextricably linked to social decisions about equity and environmental sustainability. In addition, the literature review will demonstrate that stakeholder alignment is a crucial part of any transportation decision, especially in the realm of passenger transportation. It follows that the options of either choosing a "supra-decision maker" or not explicitly aggregating decision makers are left for dealing with the reality of multiple stakeholders for the transportation domain.

To narrow the scope of past MATE studies, problems were formulated from the point of view of one or two decision makers, or from the point of view of a single aggregate "supra" decision maker instead of multiple decision makers. The complex reality in which those problems existed was acknowledged, but excluded for purpose of the analysis (Diller 2002; Derleth 2003; Roberts 2003; Ross 2003; Shah 2003; Ross, McManus et al. 2009). In one past application with multiple stakeholders (Terrestial Planet Finder), the decision problem was described in terms of several individual single-stakeholder decision problems (Ross 2006; Ross and Hastings 2006). A Pareto optimal solution for all involved parties could not be found, necessitating compromises for the project to move forward. Given a set of alternative allocations of goods or income for a set of individuals, a change from one allocation to another that can make at least one individual better off without making any other individual worse off is called a Pareto improvement. An allocation is Pareto optimal when no further Pareto improvements can be made.

2.1.2 Tradespace Exploration

Tradespace exploration is a method for understanding complex solutions to complex problems. It is a model-based tool that makes possible a low-fidelity up front assessment of the properties of many architecture concepts.

The term «tradespace» is a combination of the words «trade-off» and «space». A tradespace as understood in this thesis and in the aerospace domain is a graphical representation and database of supporting data and mathematical models of all possible solutions to a design problem. The possible solutions are created by systematically enumerating design vectors, where a design vector contains design variables that a designer can influence about a system. Ideally, a design vector would contain *all* design variables of a system. In practice however, the set may be limited to key design variables that most strongly drive the attributes that stakeholders are interested in. Key design variables can be determined by a Design Value Matrix (DVM), which is explained in more detail in section 2.1.4.1. "Trading-off" refers to the act of traversing the tradespace during the search for "better designs", utilizing any definition of "better" that is defined by the analyst, typically consisting of multiple and competing objectives. The trade-offs between different designs refer to either different levels of resources that are committed, or to different characteristics of performance that are acquired as a consequence of the amount of resources that is spent on them. "Space" could be based on the term "playspace" (Wikipedia)[4], or the mathematical term "space" as used in linear algebra. "Space" in linear algebra is the span of coordinates as defined by a set of basis vectors. The tradespace would therefore be the coordinate space of possible positions of various trade-offs. Alternatively, space could be derived from a mathematical "playspace", which refers to a multi-variant mathematical space that is used to analyze or explore its elements according to different desired criteria. The exploration part hereby denotes not simply optimization, since it can involve human interaction and creative input to the designer in how the tradespace may be broadened as a result of its actual shape, as well as the opportunity to learn about the potentially complex relationships between parameters across the tradespace. The focus on the entire tradespace prevents a designer from settling on a single or a few point designs early on in the process of conceptual design. Rather, the designer is led to keep impacts to the system as a whole in mind as design vectors are systematically varied. Through the process of systematic variation, the creative solution generation process of designing an engineering system is supported. Creativity is specifically supported by the method's guidance in the combination of different resources when generating the tradespace. The process may lead to novel combinations that the designer may not have considered before. Tradespace exploration in this sense is used at such organizations as NASA, DARPA and MIT to analyze large complex engineering projects in the aerospace domain that involve complex resource and performance dimensions and multiple goals held by multiple stakeholders (Ross, Hastings et al. 2002). An area of ongoing research at MIT, of which this current thesis is a part, is how to apply tradespace exploration to areas beyond aerospace.

2.1.3 Static and Dynamic MATE

The goal of a Static MATE study is the generation and exploration of a full tradespace of design options for a given problem, ensuring the creation of a large number of designs and their systematic exploration. Ross (2003) provides a detailed description of an example 48 step process that can be followed for conducting a Static MATE study. Dynamic MATE (Ross 2006), an extension of Static MATE, is intended to help create designs that provide value to its stakeholders in a changing environment and value context. Unlike Static MATE, Dynamic

[4] Article on "Tradespace", retrieved on 12/27/2009

MATE explores system performance across changing value propositions, as perceived by stakeholders. Value changes are likely to happen in the multi-decade lifespan of complex engineering systems, such as transportation and aerospace systems.

2.1.4 MATE process

MATE offers tools for establishing decision criteria and for generating and evaluating solutions. The method calls for a feedback loop between designers and decision makers, since iterating attributes and properties of available technical designs improves the awareness and communication of real decision maker values to designers. Naturally, the value as expressed by decision makers is influenced by their past experiences and may to some extent not even be consciously known by them. Through confrontation with the tradespaces as a result of low-fidelity technical modeling, decision makers understand the relationship between their expressed attributes and properties of available designs and may, through the increased insight, be led to change their values in a subsequent iteration. The MATE process denotes the sequence of steps of performing MATE studies and discussing the results to refine inputs for the MATE study in the next iterative step. The steps of a single iteration of a MATE study are outlined in remainder of section 2.1.4.

2.1.4.1 Set-up

The set-up step of a MATE study consists of the steps before utilities are elicited and underlying relationships are modeled. Specifically, the set-up consists of the following steps (definitions are provided at the end of the list):

1. Determine key decision making stakeholders
2. Define a mission objective (what the system is expected to achieve), including scoping decisions, context and constraints on a system
3. Elicit a list of attributes from each decision maker and valuation of these attributes as obtained from structured utility interviews.
4. Derive system architecture concepts.
5. Define design variables and constants.

Attributes can be any decision-maker perceived metric that measures his level of satisfaction with the fulfillment of system goals. MATE does not impose any constraints on the decision maker as to what an attribute could or should be. The only restriction are the six criteria that (Keeney and Raiffa 1993)establish for a set of attributes. According to these criteria, a good set of attributes should be:

Complete	Decomposable
Operational	Non-redundant
Minimal	Perceived independent

(Keeney and Raiffa 1993)

Perceived independence is not a necessary criterion; however it is strongly desirable in order to facilitate the multi-attribute utility elicitation during the MATE analysis.

Furthermore, two axioms of multi-attribute utility need to be fulfilled (de Neufville 1990). *Preferential independence* means that the order between any two levels of an attribute is independent of the level of any other attribute. This axiom makes possible the comparison of two dimensions (two different attributes) at the same time, independently of other attributes.

The second axiom is *utility independence*. It denotes that the relative intensity of value k_i for different levels of one type of attribute is independent of the level of all other attributes.

As stated before, *utility* is a dimensionless metric that ranges from the value 0 (minimally acceptable, below this threshold stakeholder will step out) to the value 1 (maximally desirable, above this threshold the attribute will not enhance stakeholder satisfaction anymore). *Attributes* are decision-maker perceived metrics that measure how well a decision-maker defined objective is met. These decision criteria are typically performance metrics that the decision maker values. For Dynamic MATE, possible future attributes are included in step 3, which may be triggered by changes in system context and are discussed with stakeholders.

Following the definition of attributes, system concepts are derived. A system concept is the mapping of function to form. The concept can be parameterized as a specific vector of design variables. *Design variables* (DV_i) are designer-controlled, tradable quantitative parameters that, as a vector DV= (DV_1, DV_2 ... DV_m) characterize a specific design. The design variables are derived from the designer's expertise and knowledge as to how an attribute can be displayed by a system, which then leads to the definition of system architecture concepts. A Design-Value Matrix (DVM), or Mapping, can be used to prioritize design variables in terms of strength of impact on attributes, as well as capturing and communicating the selection of design variables as drivers of stakeholder values. Examples of DVM use can be found in (Ross and Rhodes 2008). Figure 2-1 shows the example DVM from (Ross and Rhodes 2008). Along the top of the DVM are listed the attributes as elicited from a user. Attribute classes (0 to 4) denote the level of articulation and accessibility of attributes. Eliciting unarticulated attributes (1 to 4) in addition to basic class 0 (articulated) attributes is part of Dynamic MATE. Design variables, designer-controllable variables of the system, are listed horizontally. The mapping indicates which design variables drive class 0 attributes. In addition to the 'x', the numbers 0, 1, 3 and 9 can be used in DVMs to indicate the strength of a design variable to drive an attribute. A disconnect between stakeholder-specified attributes and designer-controllable technical variables can be detected and addressed at this stage.

			Value-space										
			Attributes										
		Articulated								Latent	Combinatorial	Accessible	Inaccessible
	Class:	0								1	2	3	4
		Silenceable	Place calls	Receive calls	Track calls	Be stylish	Be simple to use	Be durable	Conops style				
	Attribute:	X1	X2	X3	X4	X5	X6	X7	X8				
Design Variables	Telecom payload DV1		X	X	X	X		X					
	Battery DV2		X	X		X		X	X				
	Material DV3					X		X	X				
	Interface style DV4	X	X	X					X				
	Visible buttons DV5	X	X	X		X	X	X					
	Audio output DV6		X	X					X				
	Notification payload DV7												
	Memory DV8				X			X	X				
	Form factor DV9					X	X		X				
	GUI DV10	X	X	X	X	X	X						
	Camera payload DV11							X	X				
	Bluetooth DV12		X	X									
	Audio override DV13	X	X	X									
	Screen size DV14				X	X	X		X				
	Screen resolution DV15						X						
	Datacom payload DV16		X	X	X		X	X					

Figure 2-1: *Design Value Matrix (Ross and Rhodes 2008)*

2.1.4.2 Modeling relationships and tradespace generation

The assessment of level X_i of attribute X^i of any design vector DV requires the modeling of underlying relationships, including the cost relationship. These design variable-attribute models and design variable-cost models translate design vectors $DV_{1..m}$ into attribute vectors $X_{1..n}$. The models can be as crude or refined as desired and feasible within the available resources. An understanding of a basic mathematical representation of the causal relationship is however a necessary prerequisite for the development of a model in equation form. Additionally, in order to create parametric models, the modeling relationship needs to be understood in a general way and not just from ex-post fitting and extrapolation of models to available data for specific examples.

MATE models can be of different forms, for example parametric models, bottom-up models or look-up tables (the last one is not a parametric model).

The use of a *value-based* approach in MATE means that in order to evaluate designs stakeholders' perceived utility is used as decision metric. Perceived utility requires an extra step once performance of a design is calculated (the levels of attributes X_i of a design vector DV), since the increase in utility from an increase in level of attribute does not need to be linear (expressed by non-linear utility functions). The structured utility interview translates performance into utility by eliciting how much a specific level of an attribute is worth to a decision maker. Based on single attribute utility functions from utility interviews, the coefficients K and k_i are derived which allow the formulation of the multi-attribute utility function U (Keeney and Raiffa 1993). The relationships formulated by the end of the modeling phase (design variable - attribute relationships) together with the utility models from the previous section are sufficient to graphically display designs in a tradespace.

$$(DV_1, DV_2, \ldots DV_m) \xrightarrow{\text{Technical and cost models}} (X_1, X_2, \ldots X_n) \xrightarrow{\text{Utility models}} U(X)$$

Figure 2-2: *Overview of calculations for tradespace generation*

Utility (benefit) and total lifecycle cost (cost) have often been used as high-level decision metrics in prior MATE applications. The multi-attribute utility U(X) (y- axis) was displayed against overall lifecycle cost C(DV) (x-axis) in a tradespace. Each point in a tradespace represents a possible design concept, represented by a design vector. If the tradespace is large, random sampling can be used to understand the shape of the tradespace while reducing computation time.

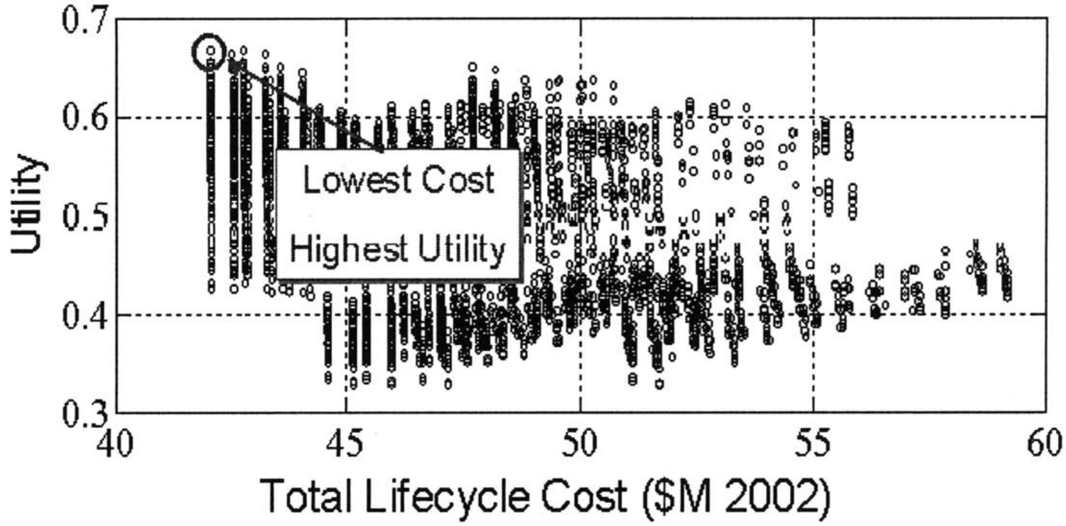

Figure 2-3: *Tradespace for space example (Ross 2003)*

The examples in Figure 2-3 and Figure 2-4 illustrate how tradespaces are read: The Pareto front consists of design concepts that are non-dominated in terms of utility (highest utility for all given levels of cost). The Pareto front in Figure 2-3 consists of the single indicated point. For applications in the transportation domain the exploration of system design utility (often describing benefits) against *several* undesirable attributes (multiple cost types, in addition to monetary cost) becomes important. Those attributes that the designer wants to keep at low levels, like development time or emissions, come at "expense." The idea of expense is akin to the idea of negative utility. The idea of Single-Attribute Expense Functions (E_i (X)) was proposed by Diller in the context of space system development expenses (Diller 2002). For applications to the transportation domain, example attributes that constitute "expenses" (negative utility) are increased safety risks, noise, pollution, and other externalities. Single-attribute expense functions (Figure 2-5) and multi-attribute expense functions work analogously to single-attribute utility functions, with the difference that more expense is worse, whereas more utility is better. Attributes that represent scarce resources to be spent or harm incurred may be more appropriate to aggregate into an expense function together with other undesirable attributes, rather than into a multi-attribute utility function. An ideal design would therefore have the coordinates (E(X)=0, U(X)=1), indicating maximal utility and minimal expense.

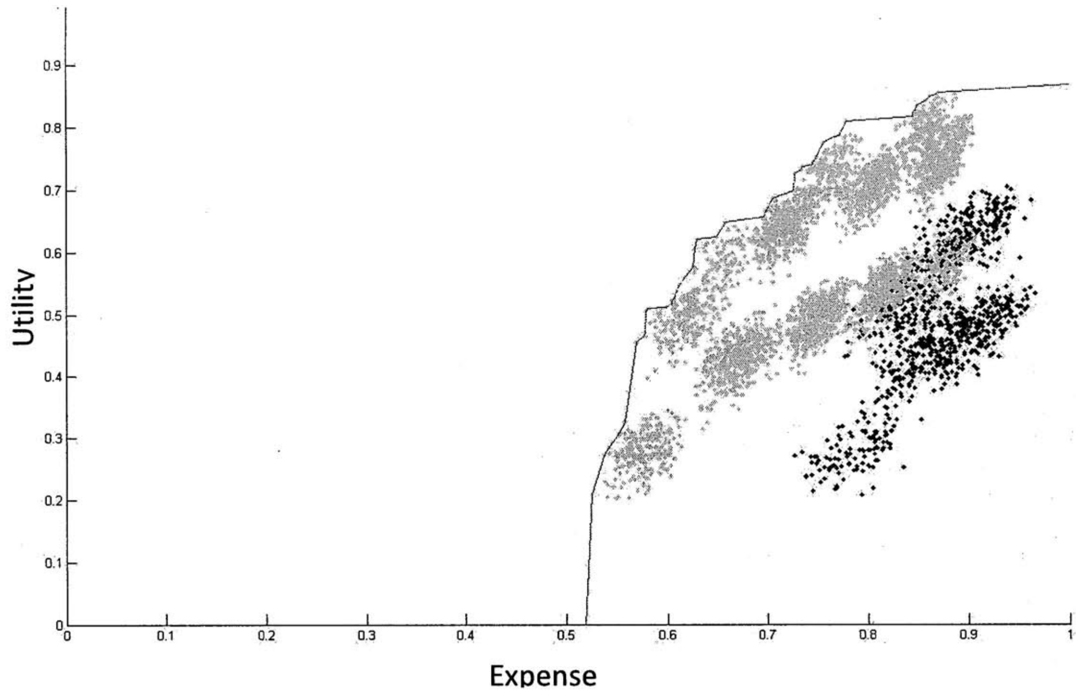

Figure 2-4: *Tradespace and Pareto front for transportation example (color coded by transportation concepts)*

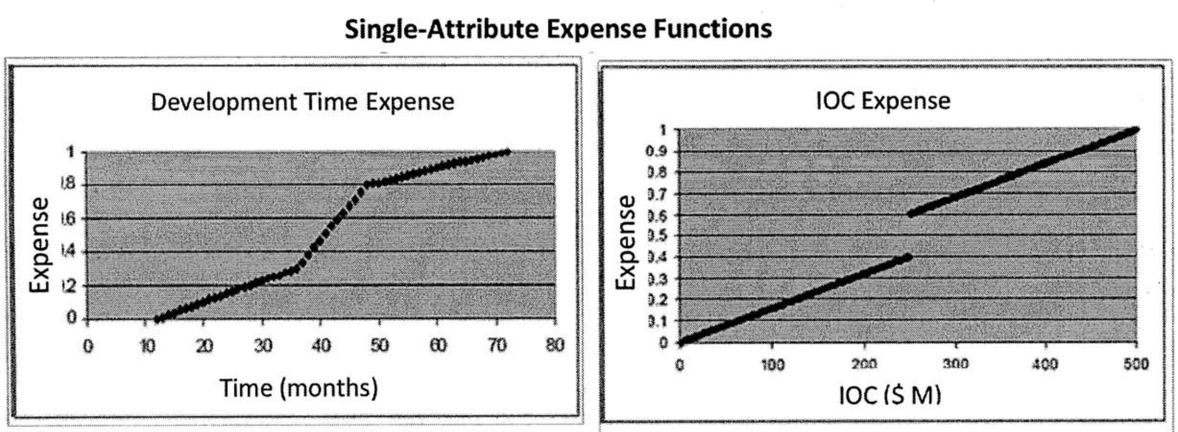

Figure 2-5: *Examples for Single-Attribute Expense Functions (Diller 2002)*

2.1.4.3 Evaluating designs

After a large number of designs have been generated in the previous step, next these are evaluated in terms of the extent to which stakeholder-valued attributes are delivered. MATE uses perceived, possibly non-linear, stakeholder-value as decision-metric, as captured by the extra step from performance to utility.

Static MATE is a descriptive method in that it aggregates and visualizes a large amount of data, and makes it useful for decision makers. While there is no concrete decision rule, analysis techniques exist to evaluate designs. Important sets of questions that guide tradespace exploration include the following:

1) What is a good design? Based on which criteria is a design considered "good"? What is the impact of individual design variables on value delivery and expense? Good design concepts can for example be revealed if "good" designs in a tradespace share common features or architecture concepts. How sensitive is the tradespace to model assumptions and assumed constants? If the tradespace is very sensitive to model assumptions, they may need to be reconsidered. The goal of the first set of questions is to develop confidence in the tradespace.
2) What is a good design for each decision maker? When presented to decision makers, are they comfortable with their Pareto-optimal designs? Pareto-optimal designs offer best utilities for a given cost level, or lowest cost for given level of utility. If decision makers are not comfortable with their Pareto optimal designs, value is not properly captured and needs to be refined in a next iteration.
3) What value do Pareto-optimal designs for one decision makers deliver to other decision makers? Which designs belong to the Pareto surface (multi-dimensional Pareto front for multiple decision makers, indicating designs from which no Pareto improvements for any decision maker are possible) Are there joint Pareto optimal designs for multiple decision makers? If not, what is a good compromise design across multiple decision makers? What does each stakeholder need to give up for reaching the compromise? Can constraints be relaxed, for example for compensation of stakeholders? Are there any real conflicts of interest, meaning that stakeholders are interested in different (or even opposed) things?
4) When using Dynamic MATE: What are good (passive) value-robust designs over time? Ross and McManus (2009) discuss insights that can be gained from multi-epoch analysis, which is a part of the toolbox of Dynamic MATE. In multi-epoch analysis,

tradespaces are explored at different points in time to determine designs that deliver value in the presence of changing contexts and stakeholder values. .

Following a MATE analysis, a number of promising design concepts may be passed on to the next detailed level of inspection and potentially discussion and reiteration. MATE provides a broad, low-fidelity assessment of different designs. The results feed directly into any successive and more detailed analysis.

Past applications of MATE are summarized by Richards (2009) as follows:

> MATE has been applied to over a dozen (mostly aerospace) systems to date and utilized in research examining requirements generation (Diller 2002), policy uncertainty, space system architecting and design (Ross 2003), concurrent engineering (Stagney 2003), spiral development (Roberts 2003), evolutionary acquisition (Derleth 2003), modularity (Shah 2003), orbital transfer vehicle design (Galabova 2004), and value robustness (Ross 2006).
>
> (Richards 2009)

Richards (2009) and Viscito (2009) studied the assessment of the properties survivability and flexibility by using MATE on examples in the defense domain. Chattopadhyay (2009) proposes a methodology for exploring Systems-of-Systems tradespaces based on MATE.

2.2 Characterization of transportation planning

Section 2.2 seeks to provide a high-level overview to the reader unfamiliar with the transportation domain of typical issues that arise in transportation decision making.

2.2.1 History of transportation planning in the US

Transportation planning can be defined as the development and evaluation of options for the siting, design, construction and operation of transportation facilities, and the decision making about a desired option for implementation. The following overview for transportation planning and strategy development over time is taken from (Dunn and Sussman 2008). They characterize how surface transportation planning in the US changed from a purely technical, cost-driven activity that served to execute political will to one in which strategy development is removed from the political arena and lies largely in the hands of planners, subject to political approval.

They point out that the deliberate transportation strategies as developed by governmental planning bodies rarely resemble actual investment decisions.

Early *transportation planning* efforts were distinct from what we would today call *strategic planning* (or strategic transportation planning). (Banister 1994) argues that US transportation planning efforts in the mid-20th century lacked "clear theoretical foundations". Instead, transportation planning was, in its early stages, a strictly technical activity facilitating the largely political objective to complete a national road network. The foundations of transportation planning were in civil engineering, transportation planners used engineering principles to analyze and select the lowest-cost routes for highway facilities. Deliberate strategy development during that era was still largely the domain of elected leaders at the state and national levels, while transportation planning was seen as a technical activity to support the execution of those politically-determined strategies.

As vehicle and infrastructure technology improved and transportation networks grew more complex in the latter half of the 20th century, transportation planning processes were continuously refined. At first, residents objected to the highway-focused approach of a civil engineering-dominated field in the late 1950s and 1960s. This led to the "opening" of the transportation planning process from a strictly technical, engineering activity to one that incorporated the perspectives of other interest groups (Gakenheimer 1976). Wildavsky (1973) reflects the opening of transportation planning during that era by defining the term *planning* as future control, cause, power, adaptation, process, intention, rationality, and even faith, each of which transcends a purely technical perspective. The 1970s saw the transportation planning process expand to include, for example, community and environmental interests, trends which were eventually codified into the continuing, comprehensive transportation planning process, many of whose elements remain in place today (Federal Highway Administration and Federal Transit Administration 1997). Throughout this transformative era, transportation planning has been characterized as a formal, "rational" process (Gakenheimer 1976; Weiner 1997; Meyer and Miller 2001), reflective perhaps of its roots in engineering.

As a result, transportation planning in the US today has evolved into strategic planning; meaning that in many cases transportation planning has become the process by which organizations *develop* strategy, rather than simply a tool to support the execution of strategy. For organizations such as transit agencies, with responsibility for a single mode, strategic planning is akin to strategy development for a business competing for a market share. In the case of organizations such as Metropolitan Planning Organizations (MPOs), with the responsibility to conduct strategic planning for entire metropolitan regions considering not only multi-modal transportation but also energy, economic development, and environmental issues, the strategic planning process generates the transportation strategies that can help to achieve broader, regional objectives such as improving quality of life and competing against other regions for jobs and economic development. Although in most cases strategic decisions are ultimately subject to approval of elected and appointed leaders, the process of developing strategies has been largely removed from the political arena and placed in the hands of planners.

Today, there are few efforts to develop a deliberate (US) national transportation strategy. Instead, strategies are developed principally at two geographic scales: metropolitan (by MPOs) and state (by state departments of transportation, or state DOTs). Both MPOs and state DOTs produce long-rage transportation plans (LRTP), documents spanning 20-30 years that are updated every 3-5 years. They also both produce annual transportation improvement programs (TIPs), which prescribe specific investments over a period of 3-5 years (Federal Highway Administration and Federal Transit Administration 1997). Organizations such as toll and turnpike authorities, and mass transit agencies also perform strategic planning activities that tend to focus on narrower geographies. Multi-state cooperatives engage in some strategy development efforts that focus on broader geographies, although such efforts are rare. [...]

Although many elements of the strategic planning process for MPOs and state DOTs, including the various products of the process, have been specified legislatively, it is through the strategic planning process, not the political process, that strategies for surface transportation are now largely developed.

Despite efforts to strengthen and formalize the strategic planning process, according to (Cambridge Systematics and HDR 2007), the linkage between strategy development and strategic decisions is still weak in many places. The study evaluated the relationships between the formal plans resulting from the strategic planning process of MPOs and state DOTs and the actual programmed investment decisions made by the same organizations, concluding that the linkage between strategic planning and programming is "often indistinct, indirect and difficult to evaluate." The authors suggest that the products of the strategic planning processes may have little impact on the actual strategic decisions, such as investments in the transportation system. In other words, the deliberate strategies developed by MPOs and state DOTs rarely resemble the emergent transportation strategies of metropolitan regions and states, at least as measured by investment patterns.

(Dunn and Sussman 2008)

It follows from this overview of the situation in the US that it is hard to point out who actually possesses which kind of decision making power about transportation decisions in the US. Decision making is de facto carried out by planners, but subject to approval from policy makers who are under various informal influences from non-decision making stakeholders. It is through the planning process in government bodies that transportation decisions in the US are made, whereas political decisions only translate weakly to actual transportation decisions. This ambiguity is also reflected in the various competing models seeking to describe how transportation decisions are made, which are discussed in the next section.

2.2.2 Transportation planning models

Central for the development of transportation planning has historically been the *rational planning model.* (Luzzi 2001) provides a description and literature review of this method. The rational planning model follows the six steps of

1. Verifying, defining and detailing the problem (problem definition, goal definition, information gathering);
2. Establishing evaluative criteria (measurements to determine success and failure of alternatives);
3. Identifying alternatives to achieve goals;
4. Evaluating alternative policies;
5. Implementing the preferred alternative;
6. Monitoring and evaluating outcomes and results.

(Luzzi 2001)

A variety of criticisms of the rational planning model are based on doubts regarding several embedded assumptions. The following criticisms 1 and 2 of the rational planning model are based on the literature review by Luzzi. Alexander (1984) provides a more complete review, which Luzzi calls an "encyclopedic array of attacks" on the rational planning model.

1. The "goal" that should be defined in the first step is assumed to be unambiguous and clearly definable.
2. The decision maker is assumed to act exclusively in the capacity of rational technician, ignoring other roles such as "advisor, mediator or administrator" (Luzzi 2001).

Another assumption is the sufficiency of available resources:

3. Enough resources (money, time) are available to evaluate all generated alternatives according to the established evaluative criteria.

The Wikipedia article on the *Rational Planning Model* (Wikipedia)[5] additionally suggests the following assumption:

4. Stable preferences over time.

MATE is based on the rational planning model, but eliminates the assumptions that preferences need to be stable over time and the assumption that the decision maker acts exclusively in the form of rational technician- in as much as prioritization over his multiple roles are revealed through a personal attribute and utility interviews. Assumptions number 1 and 3 however remain embedded in the method.

Frederick Salvucci, former Secretary of Transportation for the Commonwealth of Massachusetts under Governor Michael Dukakis (1975-1978, 1983-1990), former transportation advisor to Boston Mayor Kevin White (1970- 1974) and Senior Lecturer at MIT in courses in Urban Transportation Planning, and Institutional and Policy Analysis, taught a 12-step model for transportation decision making in the course ESD.225 "Urban Transportation Planning" (Salvucci and Murga 2008) at MIT. The 12-step model is informed by his extensive experience in politics and practice and adds considerations of political feasibility and potential for coalition building to the rational planning model (**original steps of rational planning model marked in bold**).

[5] Retrieved 08/26/2009, 2009

12-step model (Frederick Salvucci)

1. Scan the environment, review history, identify trends, project future conditions;

2. Identify relevant actors, institutions, primary roles and interests;

3. **Define problem(s);**

4. **Develop solution(s);**

5. Consider implementation;

6. **Predict outcomes, benefits, costs, impacts;**

7. Consider operation and maintenance of facilities, services;

8. **Evaluate alternatives;**

9. **Choose course of action;**

10. Build constituency, consolidate allies, convert enemies;

11. Implement;

12. Operate and maintain.

Other models for transportation planning

Other models describing decision making behavior, in addition to rational planning, have been suggested to describe the reality in which transportation decisions are made. Depending on assumptions of the influence that decision makers can exert on their environment, these models contain a prescriptive element if those people who make decisions also have the power to implement the changes that they decide upon. These additional models include satisficing, incremental change, organizational process, and political bargaining.

As described before, *rational planning* is the process of establishing evaluation criteria for a specified problem, generating a set of alternatives and subsequently evaluating alternatives. *Satisficing* is a decision making process that aims for acceptability of a solution, not optimality. The method seeks to factor into the decision the cost for information gathering and processing by accepting the first solution to meet a specific set of criteria.

Incremental change is the decision making process that results from a situation in which only a limited number of alternatives can be identified, and the consequences of those alternatives can only be evaluated to a limited degree. In addition, multiple decision makers are not in a position to coordinate effectively. As a result of this constrained solution space, change happens in marginal increments and is directed away from problems, but not towards any overarching specified goal.

Organizational process is a description of the decision making process that seeks to model the multiple factors that come into play when people interact in organizations. While the process is goal-oriented, the actual goals that an organization eventually pursues emerge from goals that relate to the problem at hand as well as individual, group, and organizational goals of the involved individuals.

Political bargaining describes a decision making process using the tools of public choice. Decisions result from the behavior of mostly self-interested agents (most importantly, those with public mandates such as politicians and governments). Their behavior can be represented in a number of ways, including utility maximization, game theory, or decision theory.

Meyer and Miller (2001) provide the following overview over the characteristics and embedded assumptions of the different decision making models in their textbook *Urban Transportation Planning*. The fact that the models for decision making processes suggested in the literature differ so much illustrates different experiences and the difficulty in assessing factors such as choosing a preferred action from a set of alternatives, considering the cost of information processing and implementation constraints brought about by individual interests and the complex behavior of organizations.

Table 2-1: *Overview of transportation decision making models (Meyer and Miller 2001))*

Decision Making Model	**Decision-making behavior assumed**	**Characteristics of the decision-making process assumed**
Rational Actor	Alternatives are selected to attain some set of pre-determined goals and objectives in a utility-maximizing manner	All relevant alternatives are considered. Decision-makers can attain a comprehensive knowledge of the impacts of each before making a decision. The evaluation criteria used can differentiate accurately among the choices considered. Alternatives can be ranked, and an "optimal" alternative can be selected.
Satisficing	The first alternative to meet some minimal level of acceptability is selected	It is impossible to generate all feasible alternatives and compare them. Alternatives are sequentially discovered. Decision-making is goal-oriented but adaptive in

		nature. The underlying choice is rational but is constrained by available resources and the ability to acquire and process information.
Incremental Change	Decision-making is geared toward moving away from problems rather than toward the attainment of objectives. Decisions are made on the marginal differences in their consequences. Actions are remedial in nature, addressing present problems, not future objectives.	Both the number of alternatives and consequences that can be identified are limited, meaning only a small number can be considered. There is limited coordination and communication between decision makers. Decision makers tend to focus efforts on policies differing marginally from those existing. There is no "right" solution, but a continual series of responses to problems. Problems are continually redefined to make them fit solutions.
Organizational Process	Decisions are highly influenced by organizational structures, channels of communication and standard operating procedures (SOPs).	Government action is the output of organizations. Organizational goals are important in the choice process, as members bargain to satisfy their own goals. Operating routines define the range of alternatives open to decision makers. Alternatives are initially proposed by organization units with their own perceptions of problems. Selected policies can only be successful when the units chosen to implement them have the capacity to carry out the policy.
Political Bargaining	The decision process is pluralistic and is characterized by conflicts and bargaining.	The large number of actors involved in decision making, with diverse goals, values, and interests, creates conflict and a need for bargaining. Outcomes of the process are not "optimal", but represent those aspects of a problem on which decision makers can agree. Controversial problems or issues tend to be ignored or put off for future discussion.

2.2.3 Stakeholders

Stakeholders as mentioned in section 2.1 play a crucial role in transportation decision making and are discussed in more detail in this section. Over 30 definitions of the term 'stakeholder' demonstrate that the concept is hard to define in its entirety (Mitchell, Agle et al. 1992). This thesis understands as a stakeholder "*every individual or group that is affected by the level of a* *system's value or harm delivery.*" Value is delivered by those effects that a stakeholder seeks to increase, whereas harm results from effects that a stakeholder seeks to keep at a minimal level. In transportation planning, three types of disadvantaged stakeholders are important in addition to stakeholders with legitimate decision making power. *'Losers'* are stakeholders that are affected by an enterprise's externalities, but do not receive any value from the enterprise's activities, such as residents who live close to airports but who do not fly. Externalities include noise, pollution, increased risks for accidents, visual impairment, and forced relocation. For an extensive discussion of externalities see (Sinha and Labi 2007). *Forced stakeholders* do not choose to have a stake in the system, but are forced by the decisions of others, such as adjacent communities to transportation facilities. *Stakeholders without decision making power* can be either without formal or without any decision making power.

Since there are typically more stakeholders with formal or informal decision making power than can be treated in an analytic decision and design method, the most important stakeholders need to be identified (stakeholder salience problem). Since stakeholder identification and salience is not supported by clear-cut guidance and best practices (Rebentisch, Crawley et al. 2005), experience, intuition and knowledge play an important role. Experience shows that if even small and seemingly insignificant stakeholders have the power to severely impact a system's design process or its operations, then their interests should be considered in the system's design. Mostashari and Sussman (2005) propose a specific categorization for transportation stakeholders, which helps to identify stakeholders for different transportation contexts: influence/power, stake, and knowledge. They distinguish stakeholders with economic/political influence (high stake, medium to high power and differing levels of knowledge), knowledge-producers (low stake, low power, high knowledge), and other affected stakeholders (high stake, low power, differing levels of knowledge), and extensively enumerate examples. The ability of 'losers' to disrupt a system shows that a transportation system's performance depends on a basic confidence in the consideration of all important stakeholders of the system, including those with no formal power.

2.2.4 Ownership

The following section on ownership refers extensively to the chapter on 'Privatization and Deregulation' with regards to airports in (de Neufville and Odoni 2003). Air transportation has experienced privatization to a larger degree than surface transportation in the US, and is therefore a suitable example to explain arising issues. For airports in the United States we face a situation in which control and ownership are very dispersed, typically among hundreds of organizations, unlike in most other countries of the world. In the US, in accordance with the national tradition of local control, individual cities, counties, and state agencies own and operate commercial airports. "Authorities" are special governmental units that operate government-owned transportation facilities, such as airports or public transportation systems. They are controlled politically by state governors and legislatures. Before the privatization of airports there was little connection between the service an airport provided and hence its expenses, and the revenues an airport earned. The desire to emphasize economic performance and customer service were the rationale for the government to privatize airports, in addition to a considerable injection of capital into the governmental budget. The character of many airports as natural monopolies however raises public concern and calls for some governmental regulation to prevent monopolistic pricing Cohen and Coughlin (2003) claim that the network effects and interdependence of airports in an airport system are another reason that justifies a decision making authority above the level of individual airports, such as a governmental body, since local planners do not necessarily have a full overview over the system-wide effects of their actions.

De Neufville and Odoni (2003) define privatization as the transfer of *some ownership* rights. Ownership implies two basic categories of rights:

1) Right to residual income, meaning profits, and

2) Management control, which covers the range from short-term operational to long-term development issues.

The second right is most important for the development of facilities. Management control means the ability to run and develop property. This includes the planning of new facilities, design of these elements, financing of capital costs and daily operations, operation of activities, the pricing of the services an airport offers, and access to transportation services. Typical privatizations of airports have not given the new owners complete management control. In particular, governments often retain the control over the development of facilities and over the pricing of concessions. This fact explains why state and federal governments have the final say over the airport development plans that airport authorities prepare. The government may prevent the building of runways and buildings that it does not want, and through this aspect of management influence other aspects of management. However, a government can only 'veto' the building of a piece of property; it cannot force an airport to carry out certain projects.

Despite the governmental ownership of airports in the United States, many different private groups like airlines, catering companies, baggage handlers, rental car agencies, parking specialists, and others routinely handle the majority of activities around an airport. Consultants prepare Feasibility and Environmental Impact Studies, engineers and architects in private practice prepare almost all of the design of facilities. Even large airports do not have the number of current projects that would warrant their own engineering staff, so that these tasks are outsourced. Major investment banks and airlines have their stake in the funding aspect of airport development. The funding comes from different sources, which is a mix of bonds, airports fees from passengers and airlines, and federal and state grants. Airlines often assume the role of guarantors for bonds through long-term leases. It follows that investment banks and airlines have immense control over airport development, since they can provide or pull the funding. In the same sense, the FAA and state governments have influence over the development of airports through their decision authority over the provision of grants.

2.2.5 Power structure

The tradition in the US is that essentially all stakeholders in an issue have the right to participate and make their voices heard. This process of overt discussions among all stakeholders of transportation distinguishes the US from other countries who have more centralized traditions, for example France or Portugal. In all transportation branches in the US, the public has the right to review planning documents, ask questions, and participate in public hearings. Environmental Impact Statements (EIS), required by the National Environmental Protection Act (NEPA) of 1996 and intended to ensure mitigation of adverse environmental effects, are published in a draft version first, and only finalized after public review.

The power structure and means of influence among the financing stakeholders of a transportation project is a complex one because of multiple unofficial relationships of dependence and influence. Airlines at many US airports, for example, act as guarantors for bonds that airports issue, and thus effectively have veto power on important structural decisions concerning airports, and, consequently, are often involved in financing and designing facilities (de Neufville and Odoni 2003). Private operators and private investors in surface transportation projects acquire influence over design decisions through their ability to co-finance transportation projects, even if this occurs with the sole interest of achieving a satisfactory return on investment.

Since communities can make the life of transportation planners miserable, planners have an interest in working together with them so as not to risk law suits and costly delays of projects. Depending on the size of the project, public outreach can happen through a single public hearing, the establishment of a stakeholder liaison office, or initiatives that fall in between. The power of local communities depends to a large extent on their connection to political representatives. Political representatives can ultimately, possibly through a higher political layer, exercise powerful influence on the planners and managers of transportation facilities. For public transportation, cities and communities have to apply for grants for capital improvements. Through the process of reviewing and deciding about the financing, the respective departments at DOTs at the state and federal levels exert influence. For the airline industry, the FAA assumes a consultant role in the planning process. It can support, encourage and confirm local decisions, but it cannot impose its will. The FAA has, however, a lot of power on the projects through the allocation of federal and state grants. Since the budget of the FAA depends on Congressional decisions, senators in return can exercise influence on the FAA's decisions through the threat to block FAA funds (de Neufville and Odoni 2003). Deep insight into the power structure is necessary to explain who is making what decisions in transportation planning processes.

The information in the remainder of this section was provided by air transportation consultant Camille Bechara of Parsons Brinckerhoff Consult Inc., who is based in Boston and has extensive experience in consulting to airports, specifically Boston Logan International. The state government is closest to the task of overseeing a fair treatment of stakeholders in the decision making process. If an airport for example fails to react to public concerns, a state government can force an airport to work together with the community, even though it cannot impose design decisions. If externalities are the reason for unhappiness, the government can, for example, ask the airport, in its comments on environmental reports, to conduct additional studies, and to work together with the community on abatement strategies for these externalities (Bechara 2008).

A consensus will be reached ultimately in transportation planning through intense negotiations between stakeholder groups. The process will take as long as it needs, which is part of the explanation for the long duration of major transportation projects' planning and implementation.

Ultimately, both the planners and the public can try to impose their interests through lawsuits, which is a known mechanism for prolonging the execution process in many cases (airport expansions, such as Boston Logan, are examples), effectively blocking a project. This circumstance adds the consideration of acceptance by stakeholders with de facto veto power to the basic engineering considerations of Will and Resources. Unlike the Highway and Airport Trust Funds in the US, there is no continuous funding program for capital improvement in public transportation in the US. A capital bill for improvement beyond recurring subsidies for operating costs is a relatively large political act. The funding dynamics are therefore less fortunate for the public transportation industry, but the basic steps of public involvement remain the same as for longer haul transportation industries.

2.2.6 Complexity

Literature explains why transportation planning is anecdotally "difficult" and "controversial" through categorizing "complexities". In cases in which new transportation structures are built and integrated with existing (legacy) systems, changes in the behavior of these legacy systems occur through coupling or emergence. These behavior changes can be anticipated or unexpected, making future behavior hard to predict accurately. A pedestrian bridge, for example, may enhance safety for non-motorized travelers but at the same time can encourage car drivers to speed, which can lead to the annoyance of residents in the neighborhood. Traffic calming measures to prevent speeding may in turn lead car drivers to discover alternate shortcuts through other neighborhoods, thereby adversely impacting those neighborhoods, and so on. The example shows the difficulty of predicting the impact certain transportation projects will have on traffic patterns. Sussman calls this kind of complexity *behavioral complexity* and defines it along with three other types of complexity that are of primary concern for so-called CLIOS systems: structural complexity, evaluative complexity and nested complexity (Lloyd 2002; Sussman 2002). CLIOS (systems), as defined by Sussman, is an abbreviation for *complex, large-scale, interconnected, open and socio-technical (systems)* (Sussman 2000). He lays out how each of these characteristics is fulfilled for transportation systems. "Complexity" means that a system is composed of a group of interrelated components and subsystems, for which the degree and nature of the relationships between them is imperfectly known, with varying directionality, magnitude and time-scales of interactions (Sussman 2002).

Structural complexity refers to a system that consists of a large number of interconnected parts.

Nested complexity is a concept that denotes that a technical system is embedded within an institutional system, which exhibits structural and behavioral complexity in its own right.

Behavioral complexity describes the fact that the behavior of systems as a result of changes cannot be predicted accurately.

Evaluative complexity suggests that multiple stakeholders exist for a system, each of whom hold different views of what are desirable and what are undesirable aspects of system performance. Even if the behavior of systems could be predicted accurately, different people will evaluate that behavior differently, making decision-making difficult. Methods for project appraisal for transportation systems need to account for these complexities.

2.2.7 Characteristics of the reality of transportation planning

As a result of the issues discussed in this section, including barriers and complexities in the planning process, transportation planning is often more reactive to the political, social, and economic realities facing a project. Meyer and Miller (2001) provide a review of the characteristics of the reality of transportation planning, citing a characterization from the early 70s.

> *Characteristics of the reality of transportation planning*
>
> 1. Incremental or tending towards relatively small changes,
> 2. Remedial, in that decisions are made to move away from ills rather than toward goals,
> 3. Serial, in that problems are not solved at one time but are successively attacked,
> 4. Exploratory, in that goals are continually being redefined or newly discovered,
> 5. Fragmented or limited, in that only a limited number of alternatives rather than all possible alternatives are considered,
> 6. Disjointed, in that there are many dispersed "decision-points".
>
> (Baybrooke and Lindblom 1970)

Even though these are the "realities" of the process, this does not mean that new methods and approaches cannot be developed to help to overcome these realities in order to move the transportation planning process into a more rational direction where feasible.

2.3 CBA as decision making method for transportation planning

2.3.1 Importance of CBA

As established in the previous section, stakeholders in the transportation domain are multiple and their values and decision making power structure are complex (large and diverse groups, forced stakeholders, stakeholders without decision making power, losers, veto-power stakeholders (government bodies, public review, regulating agencies), informal power structures through informal mechanisms (funding allocation decisions by regulating agencies, lobbying of state senators, blocking of transportation regulating agencies' funds by senators, public law suits to delay projects and drive up project cost, public protest and media campaigns). Because of the large and at times opaque distribution of power, it is hard to point out who actually makes what decisions for transportation projects.

CBA is an established method from the transportation domain to provide a somewhat fair treatment of "society at large" (an attempt at aggregating different stakeholders) and a clear decision rule for messy stakeholder objectives. Both the aggregation of costs and benefits (a variation of the utility metric as applied to society at large) and the decision criterion have been critiqued in literature, as is discussed later on in this section.

Cost-Benefit Analysis (CBA) is the process of weighing positive and negative effects of an option with the goal to come to a decision. A general decision rule is that positive effects should outweigh the negative effects, and that the option with the highest net benefits should be chosen. With no further specification, a number of different processes ranging from a "Pro-Con list" to a detailed project evaluation can be thought of as a Cost-Benefit Analysis. In the infrastructure domain, CBA often denotes a specific, government-codified process for project appraisal. Project appraisal is a generic term that refers to the process of assessing, in a structured way, the case for proceeding with a project or proposal. It often involves comparing various options, using economic appraisal or some other decision analysis technique. CBA is one of the most widely accepted methods for project appraisal for large-scale infrastructure investments in the public sector. In the US, Government Authorities such as the Federal Aviation Administration, the National Highway Safety Administration, the Environmental Protection Agency, and the Occupational Health and Safety Administration require CBAs to be performed for a variety of projects to move forward and receive Federal funding or permits (Viscusi, Vernon et al. 2000).

EU Cohesion Policy regulations require a CBA of all major investment projects applying for assistance from the Cohesion Funds, where major denotes projects between 10 million Euros and 50 million Euros, depending on the project class (European Commission Directorate General Regional Policy 2008). The practice of how CBA is executed, however, varies between countries, such as between the United States and the European Union, and sectors, for example health care and transportation. Differences exist between the impacts (positive and negative) that are considered, the extent to which they are included, the practice of monetization, and the choice of discount rate.

2.3.2 Characterization of CBA

CBA seeks to enumerate all direct costs and benefits to society of a particular design, assigns them monetary equivalents, discounts future values to a Net Present Value (NPV), and adds them to a single number. Direct costs and benefits are those that are directly experienced by stakeholders of the transportation system, such as travel and waiting time, construction expenses, crash costs, and externalities such as noise or pollution. Indirect effects are those that occur to the regional economy as a whole, such as changes in rent prices, land-use patterns, or employment generation. These effects are typically considered separately from CBA in the Economic Analysis of a project. The differences in CBA scores among alternatives allow a ranking of alternatives and a reduction of feasible designs to those that would constitute *Kaldor-Hicks* improvements. *Kaldor-Hicks* efficiency is a measure for economic efficiency holding that an outcome is efficient if a Pareto-optimal outcome could theoretically be reached by compensating stakeholders who are made worse-off by the outcome. For example, a voluntary trade would be Kaldor-Hicks efficient if a third party suffered externalities such as pollution, but the buyer and the seller would still be willing to carry out their trade even if they had to reimburse the disadvantaged third party. It is not required that the act of compensation actually be carried out, the requirement is a mental model to ensure that the net benefits are in fact greater than net costs. Therefore, the creation of losers can easily be compensated if at least the same amounts of benefits accrue to another party. Pareto efficiency requires that every participant in a trade be made better off or at least not worse-off, meaning that he must at least not be worse off after the trade. As such, Pareto efficiency is a subset of Kaldor-Hicks efficiency.

2.3.3 *History of CBA*

The practical application of CBA was initiated in the US by the Corps of Engineers, after the Federal Navigation Act of 1936 effectively required cost-benefit analysis for proposed federal waterway infrastructure (Proceedings of the 2006 Cost Benefit Conference). The Flood Control Act of 1939 was instrumental in establishing CBA as Federal policy. It specified the standard that "the benefits to whomever they accrue [be] in excess of the estimated costs" (Guess and Farnham 2000). Subsequently, cost-benefit techniques were applied to the development of highway and motorway investments in the US and UK during the 1950s and 60s. An early, and often quoted, more developed application of the technique was made to London Underground's Victoria Line. Over the last 40 years, cost-benefit techniques have gradually developed to the extent that substantial guidance now exists on how transport projects should be appraised in many countries around the world.

In the UK, the New Approach to Appraisal (NATA) was introduced by the then Department for Transport, Environment and the Regions. This brought together cost-benefit results with those from detailed environmental impact assessments.

The EU's "Developing Harmonised European Approaches for Transport Costing and Project Assessment" (HEATCO) project, part of its Sixth Framework Programme, has reviewed transport appraisal guidance across EU member states and found that significant differences exist between countries. HEATCO's aim is to develop guidelines to harmonise transport appraisal practice across the EU (European Commission Directorate General Regional Policy 2008).

Transport Canada has also promoted the use of CBA for major transport investments since the issuance of its Guidebook in 1994 (Transport Canada 1994).

More recent guidance has been provided by the US Department of Transportation and several state transportation departments, with discussion of available software tools for application of CBA in transportation, including HERS, BCA.Net, StatBenCost, CalBC, and TREDIS. Available guides are provided by the US Federal Highway Administration (2003), Federal

Aviation Administration (2006), (Minnesota Department of Transportation)[6] and (California Department of Transportation)[7].

The collection of sources for the summary in this section was taken from the Wikipedia article on Cost-Benefit Analysis (Wikipedia 2009)[8].

2.3.4 Other methods in project appraisal

CBA is one method of several methods that are typically performed in the process of project appraisal. Other important studies include an Economic Impact Analysis and Environmental Impact Analysis (in the form of an Environmental Impact Analysis or Statement), and a financial feasibility study.

Economic Impact Analysis (EIA) sheds light on likely losers and beneficiaries of a project. Methods for EIA include relatively simple qualitative methods such as surveys, market data and case studies, or more sophisticated ones such as regional economic models. From a (somewhat simplifying) economic perspective, the indirect benefits of a project are expressed by consequences to the economy, in terms of changes in rent prices or employment generation and are a transfer of the direct benefits through the operation of the marketplace of a transportation project. If, for example, commuting times from a particular neighborhood decrease and living there becomes more desirable, commuters are willing to pay a higher rent. They thereby transfer part of their benefits from faster commuting times to the landlords. It is assumed that the indirect effects are not additive to the value of the direct effects measured in CBA (US Federal Highway Administration 2003). This is the reason why CBA practice as recommended in the FHA primer only previews the quantification of direct benefits, but not of indirect economic benefits. With ongoing research in the domain of agglomeration benefits this notion may change in the future.

The National Environmental Policy Act of 1969 (NEPA) in the US requires the analysis of the social, economic and environmental impacts of any project that receives federal funds or federal approval. EIA and Environmental Impact Analysis are typically important parts in this analysis. While NEPA requires that externalities be mitigated, the CBA is typically performed before Economic or Environmental Impact Analyses are conducted. CBA can therefore inform the later

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[6] Retrieved 12/27/2009, from http://www.dot.state.mn.us/planning/program/benefitcost.html
[7] Retrieved 12/11/2008, from http://www.dot.ca.gov/hq/tpp/offices/ote/benefit_cost/
[8] Retrieved 12/27/2009, from http://en.wikipedia.org/wiki/Cost-benefit_analysis

two analyses and mitigation costs can be included in the EIA, but an analysis of environmental consequences is not performed until after CBA, and is typically not therein included.

A financial feasibility study calculates the expected Net Present Value (NPV) of a project, based on expected cash flow. If the NPV is positive, the project is warranted for reasons of profit maximization alone. If the NPV is negative, a decision has to be made about whether its non-financial benefits warrant its implementation. It should be noted that transportation projects are often not primarily profit-seeking ventures. The amount of initial and operating subsidies is however an important consideration, and (near) operating self-sufficiency can greatly help find allies for a project.

2.3.5 *Extensions of CBA*

Transportation evaluation methods have been improved and have become increasingly comprehensive, as larger frameworks were developed that seek to integrate different evaluation perspectives to give a more complete picture. The CLIOS process as described by (Sussman 2000) is one such example of a larger and more comprehensive framework for transportation planning that encourages the use of CBA and other methods such as stakeholder analysis at different steps throughout the process. On the other hand, CBA itself has been subject to suggestions for improvements. Two examples are (Wang and Liang 1995), who suggest the use of fuzzy concepts in CBA, and (Rivey 2007) who proposes the incorporation of real options thinking into CBA if the evaluated designs allow for flexible development. Recognizing these new developments, CBA as referred to in this thesis is "classical" CBA as defined by, for instance, the Federal Highway Administration in a primer on Cost-Benefit Analysis (US Federal Highway Administration 2003).

2.4 **Contrast between MATE and CBA**

Very often transportation decisions are political decisions meaning that social decisions about favoring and hurting certain groups of society are an important consideration in addition to technical considerations. CBA attempts to answer the following questions inherent in the transportation planning process: Is this a good project or not? Should we proceed with its planning or not? The reason for this expectation of prescriptive guidance is the fact that people charged with the technical design of transportation facilities are de facto also charged with the political decision of whether anything should be done at all.

CBA answers the question of whether benefits to society, as measured by a codified legitimized process, exceed the costs of the project. CBA has prescriptive elements built in that requires certain attributes to be quantified, prescribes how they should be quantified, and offers a decision rule (highest Net Present Value). CBA allows a certain transparency that helps to justify political decisions and makes possible the comparison of different designs on a common scale.

MATE is a prescriptive approach in that it asks the question: How do we deliver a system that best meets stakeholder expectations? What do stakeholders value? The technical capabilities of a system and the utility from stakeholder interviews are captured and displayed. MATE does not have any built-in prescriptive guidance, as the only imperative of what should be done is derived from the stakeholders' subjective values as elicited in interviews, as well as the decision rule selected for choosing from among the assessed alternatives. As an emerging method, MATE is not codified for decision-making processes in the way CBA is, and hence comparisons of benefits and shortcomings need to take this different codified structure into account. MATE has a solution-generating step built into the methodology, whereas CBA receives design concepts as external inputs. Conclusions regarding the creative benefits of tradespace exploration therefore regard the ensemble of CBA and whatever solution-generating methods are used prior, rather than CBA alone.

2.5 Benefits and shortcomings of CBA

There are a number of flaws inherent in CBA (Gomez-Ibanez, Tye et al. 1999, de Neufville 1990): introduction of critical value assumptions through the discounting of non-monetary goods, interpersonal utility comparisons and loss of information about the distribution of costs and benefits, and aggregation of certain and uncertain costs on a common scale. Critical value assumptions relate, for example, to practices for the elicitation of monetary equivalents for health risks or accidents, or to the discounting of future environmental damage (Heinzerling and Ackerman 2002). Heinzerling and Ackermann argue that this practice devalues the lives of future generations compared to generations today. Some practices for eliciting the monetary value of damage, such as a crash, are questionable since they assume a linear relationship between risk and willingness to pay. A person's willingness to pay to avoid a marginal risk of accident however does not need to be the same as that fraction of a person's willingness to pay to avoid a sure accident, since the utility can be non-linear. Interpersonal utility comparisons occur since costs to some parties can be hidden or offset by benefits to other parties.

The Federal Highway Administration (FHA) acknowledges in (US Federal Highway Administration 2003) that one source of error is the comparison of only one, or a limited number of alternatives, to the base case. The base case is the status quo under minimal improvement. The base case is a required option that needs to be analyzed in detail according to the cited source. In that case, the base case (minimal change) may look advantageous even though less costly alternatives exist. On the other hand, if advantageous options are left out of consideration, the analyst can (willingly or unwillingly) bias the analysis by making a suboptimal option look like the most promising one by intentionally or unintentionally leaving out a superior option. The FHA therefore recommends that "proper" CBA should consider a "full range of reasonable alternatives" (US Federal Highway Administration 2003). Without a systematic approach to exploring a larger number of feasible alternatives however, the risk of sub-optimizing always remains. The same problem applies to cases in which two projects are lumped together in one, yielding an overall CBA that may be positive or negative. In reality, however, one of the projects may be a good one whereas the other one should be rejected. It remains to the expertise of the analyst to ensure that separable projects not be lumped together as one in the same CBA.

Another shortcoming arises from the fact that very often in infrastructure projects different types of non-monetary "costs" have to be considered, typically in the form of externalities such as environmental impact, noise, health and safety risks. In CBA, these non-monetary costs (in addition to monetary costs such as construction and maintenance) are considered. CBA suggests that these costs can be properly characterized in terms of dollars and compensated for through payments or other remedies, such as constructing noise walls or installing soundproof windows. In practice, however, compensation of stakeholders cannot always be easily achieved. Monetary payments may for example be given to one generation of stakeholders, but will not be given to the next one. Similarly, environmental damage may be irreversible despite investments in environmental protection elsewhere.

Lastly, CBA loses information about the time-criticality of a project. A project may be more useful if it is put online before a certain event. In the example case that is discussed in this paper, the airport express would deliver more value to its stakeholders if it was completed before the

Summer Olympics in 2016, should Chicago have been selected as the host city. Programmatic attributes such as "project completion before 2016" cannot be included in CBA. It is possible to discount future benefits more steeply through the choice of the discount rate. That method is however a very crude way of modeling benefits since all future costs and benefits would be discounted equally steeply, regardless of their time-dependence. According to recommendations for good practices of CBA, there should not be much discretion in the choice of how costs and benefits are valued. While the monetary value of costs and benefits like reduced travel time or pollution is dependent upon local factors, agencies like the FHA, the US Department of Transportation (USDOT) and some state Departments of Transportation provide guidance about where and how to retrieve the required data to ensure comparable procedures for different projects.

Don Pickrell, as cited in (Gomez-Ibanez, Tye et al. 1999) cites two objections to CBA: First, CBA can be applied only if all of the relevant effects of a project can be measured as monetary equivalents, and only if decision makers fully agree on those measurements. If these hold, then decisions on projects can be reduced to a technical exercise. Second, he criticizes the basis on which projects that create "losers"' can be justified because of net aggregate benefits (interpersonal utility comparison).

Ultimately, transportation project evaluation is inherently political in that technical decisions cannot be made without making political decisions. CBA is an attempt to provide structured guidance in the face of this reality, but the reduction of political judgments to a technical exercise raises a large number of concerns, as laid out in the literature review in this section. The value of any particular evaluation method depends ultimately on how it informs the decision making process. It is on this basis that MATE and CBA are compared when used to evaluate the case studies in later chapters.

Chapter 3 Implementation Issues in applying MATE within the Transportation Domain

A logical first step in applying MATE beyond the domain in which it was developed is to discuss a systematic application of each successive step of the MATE set-up phase to a generic transportation problem. Issues that arise from the implementation within a new domain are discussed. Space and transportation systems are compared along five dimensions that were inspired by MATE, which reveals domain differences between the two. The depiction in this chapter purposefully includes some strong generalizations in order to caricature domain differences in order to illustrate general trends.

The systematic characterization in this chapter is important for several reasons: It is useful to be mindful of domain differences when interacting with people from different domains so as to ensure effective communication. Being aware of typical issues in different domains such as space and transportation will enable fast and effective knowledge transfer from one domain to the other, when new issues in one domain arise that have already been addressed in a different domain. An example for when quick knowledge transfer may become relevant is the development of space infrastructure and the need to consider legacy components in subsequent designs. Lastly, from the point of view of further developing MATE as a method, the discussion of systematic cross-domain application of the set-up of MATE to a generic problem makes embedded assumptions explicit, which allows for their revision and potential elimination to increase the applicability of MATE to problems across domains. Implications of areas for refinement are identified that need to be addressed when MATE is applied to a new domain. Figure 3-1 and Figure 3-2 and Table 3-2, Table 3-3, Table 3-4, Table 3-5 and Table 3-6 at the end of the subsections summarize domain differences. The five categories that are discussed in the subsections are (3.1) mission objective(s), (3.2) stakeholders, (3.3) system concepts, (3.4) constraints, and (3.5) dynamic lifecycle issues.

3.1 Mission objective (s)

The mission objective is a concise summary of the broad goals the system should achieve in operation and is derived from the essential needs that drive development of the system. It may be labeled differently in other contexts, for example simply "mission," "mission statement," "goal statement," or other. The first step in a MATE analysis is to understand the dilemma that the decision maker is seeking to solve, which is then captured in a mission statement.

Primary civil space mission objectives include communications, navigation, weather surveillance, scientific observations, and space exploration (Larson and Wertz 1992). Military space mission objectives include tracking, imaging, precision, navigation and timing. The explicit incorporation of a mission objective in the design process goes back to the fact that typically a single institution (e.g., US Department of Defense, NASA, or European Space Agency) is in charge of capturing user needs and of formulating a mission statement. Nearly all space missions also have a hidden agenda of secondary, typically political, social, or cultural objectives.

In transportation systems, a clear mission objective does not typically precede the formulation of goals. Rather it is emphasized what should be taken into account when operating the transportation system, but not what should ultimately be achieved. (Sinha and Labi 2007) propose a pyramid of desired outcomes for a transportation project with three *overall goals* at the top that are meant to broadly describe "what the transportation action is meant to achieve" (Sinha and Labi 2007), p. 21). The three goals are Efficiency (is the output worth the input?), Effectiveness (is the action producing the desired outcomes?), and Equity (are diverse segments of the population receiving their fair share of the action's benefits?). The three goals can be summarized as "Three E's" (Figure 3-2). While desirable in every system, these overall goals are different from a mission objective in that they do not explain the purpose of the transportation project, the captured need that the project is intended to fulfill.

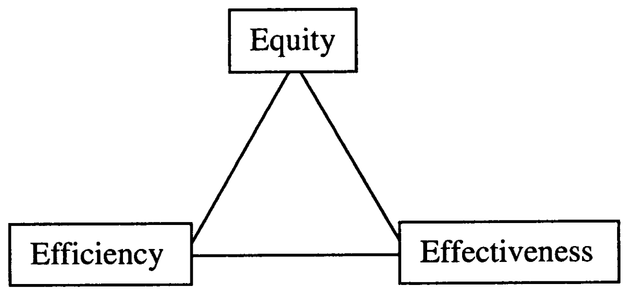

Figure 3-1: *Three E's according to (Sinha and Labi 2007)*

Another common three-parted goal set in transportation, taught in several MIT transportation graduate courses, is that of another "three E's": Economy, Environment and Equity (Figure 3-2). They describe three competing goals that a transportation system should fulfill, but that are often in direct contradiction. Economy is the desire for economic stimulation through mobility of people and goods and the enabling of profitable economic activity in an area. Environment reflects the interest in preserving natural resources. Equity refers to the role of access to transportation as a public good and societal necessity, and the recognition and compensation of adverse effects to people through transportation activity.

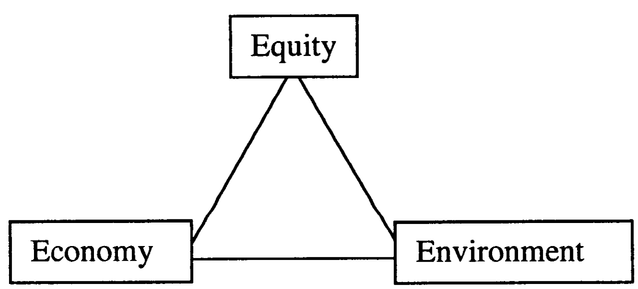

Figure 3-2: *Three E's according to Fred Salvucci*

Fred Salvucci, former Secretary of Transportation for the Commonwealth of Massachusetts and Senior Lecturer at MIT, cites the history of public transportation in the City of Boston over time as an example for how at different points in time one of the three goals was prioritized, but how the other two goals were later vehemently acknowledged as priorities shifted. Karl Haglund describes the history of transportation development in Boston in his book "Inventing the Charles River" (Haglund 2000). An example is the need for additional transportation capacity over the

Charles, which led to the planning of a 16-lane-bridge close to the current location of the Zakim bridge. Little by little, the media and individual people began to criticize the ugliness of the proposed structure and the desire to preserve the natural beauty of the open Charles River. Even later, people did not only claim natural preservation and transportation capacity, but also the preservation of accessibility of ordinary people to the banks of the Charles (equity) who could not afford to live in the vicinity.

Both concepts of "3E" enumerate criteria of *how* a transportation system should be designed and operated, but what should be achieved by a particular transportation system is not stated explicitly.

In addition to this observation from literature, section 3.6 in this chapter summarizes a collection of mission statements as expressed by different US State Aviation departments. State aviation departments are part of state Departments of Transportation (DOTs) and fulfill a variety of tasks, including supporting airport authorities in their (master) planning, developing safety programs, and administering grants and loans. The Department of Aviation of the United States' (national) Department of Transportation (USDOT) is the Federal Aviation Administration (FAA).

The mission as stated by USDOT (2008) in United States Code, Title 49, Section 101 provides an example for the multiple and competing goals that are frequently expressed for transportation planning projects: "*The national objectives of general welfare, economic growth and stability, and the security of the United States require the development of transportation policies and programs that contribute to providing fast, safe, efficient, and convenient transportation at the lowest cost consistent with those and other national objectives, including the efficient use and conservation of the resources of the United States.*"

The comparison of mission statements of state Aviation departments in Table 3-1 is not intended to compare the quality of work that an aeronautical division is performing, but to show how the understanding of the nature and purpose of mission objectives differ for a specific branch of state DOTs in the US. It should be noted that the mission statements of organizations tend to be broader and fuzzier than those for specific projects. An observation is that the mission statements in the cited example encompass both the level of a specific mission for a project and for project portfolio decisions without clear separation.

Table 3-1: *Comparison of Mission and Vision Statements from selected State DOTs and USDOT*

State and title of division	Mission/Vision/ Enumeration of tasks and responsibilities if provided
California DOT, Division of Aeronautics	*Vision*: Meet majority of needs of aviation community and general public by providing safe, efficient, economically beneficial and environmentally compatible facilities within available resources. *Mission*: Control compliance with airport safety standards, plan state aviation system, administer state grants and loans, administer noise and environmental impact regulations. *Additionally listing of primary stakeholders and customers of Aeronautics Division.*
Nebraska Department of Aeronautics	Mission: To facilitate the advancement of aviation in Nebraska. Enumeration of tasks: Provide air transportation service, plan airport construction and improvement, provide aviation education.
Texas DOT, Aviation Division	Mission/Vision for Aviation Division not provided. The only task for the Aviation Division described on their web page is the one to assist cities and counties with the applications for federal and state grants. (*Vision Texas DOT general*: To apply our collective expertise to make great things happen, through innovation, teamwork and trust. *Mission Texas DOT general*: To consistently deliver outstanding solutions that create a better world in which to work and live.)
Massachusetts Aeronautics Commission	*Mission*: Promote aviation while establishing and maintaining a safe, efficient airport system to meet the current and future air transportation and economic needs of the Commonwealth. *Enumeration of tasks*: develop and plan airports, promote aviation safety, investigate aircraft accidents, plan aviation, certify and license airports and airport managers.
New Jersey DOT, Aviation	*Mission*: Foster the development of an efficient air transportation system that responds to the needs of its users and the public. (*Mission DOT general*: Improving Lives by Improving Transportation.)
Colorado DOT, Division of Aeronautics	*Mission/Vision* (statement not labeled): Support the DOT's development of a forward-looking multi-modal transportation system in the 21st century through the promotion of partnering with the DOT's public and private constituents to enhance aviation safety, aviation education, and the development of an effective air transportation system through the efficient administration of the Aviation Fund.
Illinois DOT, Division of Aeronautics	*Mission*: Maintain and upgrade the state's airport system. *Responsibilities*: develop aviation safety programs, provide aviation education and publication, provide emergency medical transportation, assist Civil Air Patrol.
USDOT, FAA	*Mission*: to provide the safest, most efficient aerospace system in the world. *Vision*: to improve the safety and efficiency of aviation, while being responsive to our customers and accountable to the public. *Stated values* are safety, quality, integrity, and people.

The following conclusions can be drawn from the look at mission objectives at state DOT aeronautical divisions in Table 3-1.

1.) The mission objectives as expressed vary a lot in nature and scope. There is no clear cut common understanding of a mission objective and its purpose. It appears that there is mainly a common understanding that a mission statement should be provided and it mostly is. Explanations of why and how projects should be done tend to be merged.
2.) The multi-goal character of airport planning, and transportation planning in general, becomes obvious. A number of mission objectives expressed the desire to provide transportation capabilities, and to operate them in a safe, environmentally conscious, socially responsible, and cost-efficient way. The decision of how to trade these different goals is however a political one and the prioritization is up to current decision makers and not captured in most statements (except where only one goal is provided, for example for Texas and Nebraska).
3.) All mission objectives seem to agree more or less explicitly that their mission is to meet demand for air transportation. Capacity expansion is however not the only possible answer to demand. In the discussion about a possible expansion of Schiphol Airport in Amsterdam, the Dutch Parliament requested the installment of an interagency project called Future Dutch Aviation Infrastructure (TNLI). The goal of TNLI was to address through extensive deliberation with stakeholders the central question of whether the Netherlands, after weighing necessity and benefits, wanted to accommodate future growth of civil aviation in their country at all (van Eeten 2001). Similar discussions occurred in other European countries, including Germany and the UK (Grayling and Bishop 2001; Upham, Thomas et al. 2003; Bickenbach, Kumkar et al. 2005). No such concerns are addressed (and if to be refuted) in the mission statements of US state DOTs. The desirability of additional airport capacity currently does not seem to be an important point of discussion in the US. However, American authors point out that airport expansion is costly, complex, and controversial. Cohen and Coughlin (2003) cite the expansion of St. Louis-Lambert International Airport as an example and study the socio-economic impact. Phase 1 of the capacity expansion at St. Louis-Lambert, which took place in 2003 and consisted mainly of the addition of a new runway, cost $1.1 billion, required the acquisition of 1,500 acres of land, which ignited protests from affected homeowners and businesses, the reconfiguration

of seven major roads, the movement of some airport support operations and the Missouri Air National Guard facility, and the construction of a new school. The authors conclude that taxing and congestion pricing would have been an efficient alternative from a socio-economic point of view. Just as congestion management including weighing the benefits of adding capacity and pricing congestion, including in the US (Gomez-Ibanez, Tye et al. 1999), so too may the desired level of growth of airport capacity emerge as point of discussion in the US and other countries where it is not currently debated.

All in all, in aviation and in other branches of transportation the "mission objective" does not seem to have emerged as a well-defined, integral concept of project planning in the same way it did in the military, space, and business communities. Instead, the mission to meet demand is often implied and a number of competing goals are enumerated with a pledge to more or less reconcile them. Possible reasons for this difference are discussed below.

Possible Reasons for less emphasis on mission objective in transportation planning process

1. Multiplicity of interests. The more specialized the capability of a system, the smaller the number of people interested in it. Transportation systems serve a broad range of interest groups through all parts of society and the economy. Unlike space systems, they could have very *noticeable* negative impacts for large parts of the population, which are discussed in the following section on stakeholders. The number of stakeholders and stakeholder groups is typically greater for transportation than for space, and their interests are more varied and controversial. Goals and objectives in transportation systems are generally developed through extensive examination of top-level agency requirements, by soliciting the perspectives of users and other stakeholders and by outreach to the general public (Sinha and Labi 2007). The mission objective in transportation systems therefore tends to be more difficult to define and to justify than in space systems, since different users value contradictory aspects and are differently negatively or positively impacted by certain initiatives.

2. Mission objectives can be a sensitive matter. Since transportation investments are a prime public policy lever, the mission objective can be unarticulated, sensitive, or even not consciously known by decision makers. Infrastructure investments such as airports are used as measures to boost employment and economic development in a certain area both through the construction work itself and the expected benefits from a strong infrastructure. Examples for such 'pet projects' include the replacement of the control towers in Nantucket and Barnstable, Massachusetts, for $ 8B. These towns are the home to the senators at the time who made the requests, Sen. Ted Kennedy and Sen. John Kerry. The planning for a new airport for $3.5B on the remote island of Akutan, Alaska has also started, as requested by Sen. Ted Stevens, Alaska. The airport would be used primarily by a large seafood company that funded Stevens' election campaign (CNN Politics 2008). Rietveld and Bruinsma (1998) further note that one must not underestimate the attraction exerted by successful symbols like fast growing airports on companies considering a new location. The mission objectives can be highly sensitive in a political environment and may be intentionally left not explicit.

3. Enabling nature of transportation hides mission objective. Infrastructure, by definition, is the "resources (as personnel, buildings, or equipment) required for an activity" (RoadStats 2008). The definition underlines the enabling character of systems such as transportation, communication, energy, and other infrastructures. Often some mission objectives are implicit in transportation system concepts, which is not true to the same degree for space systems. For example, implicit in the concept of train is the movement of people and freight between two points along the rail. Implicit in the concept of an airport is the provision of safe access for people and freight to air transportation. No such expectations exist for space systems.

4. Differing importance of Equity. An important consideration in transportation planning is equity, illustrated through the fact that it is the only common component of both "three E" frameworks. In welfare economics, equity can be distinguished from (purely) economic efficiency in the overall evaluation of social welfare of an outcome. Although the term equity has broader uses, in the context of welfare economics it is used as a counterpart to economic inequality in yielding a "good" distribution of welfare. Since the notion of an equitable outcome is related to human perception of justice and fairness, it is hard to define equity in an objective way. Informally, equity means that all involved parties receive their fair share of an action's benefits, recognizing that "fair share" calls for further deliberation. While the crossing of territory of an uninvolved party is a classical problem for transportation, including the subsequent issue of fairness, this type of problem does not usually arise for space systems. Typically decision and design methods originating in the space domain do not make judgments about the issue of fairness or distribution of benefits and costs, and make an implicit weighting of relative importance of stakeholders. Space mission methods require the definition of mission objective(s) as input, and help to make better decisions for fulfilling those explicitly defined objectives. The problem in transportation is to evaluate ways to better a current situation while minimizing the impact of negative externalities to ensure a balanced realization.

Table 3-2: *Comparison of "Mission Objective(s)"*

Mission factors	Space	Transportation
Defined Mission Objective	Integral part of design process	Typically not made explicit
Equity	Typically not considered	Essential to consider

3.2 Stakeholders

Explicit consideration of disadvantaged stakeholders in transportation. As was hinted at in Chapter 2, three types of disadvantaged stakeholders are important for transportation systems that are not typically considered for space systems.

'Losers' are stakeholders that are affected by an enterprise's externalities, but do not receive any value from the enterprise's activities, such as residents who live close to airports but who do not fly. Crossing a third party's property often includes noise, pollution, increased risks for accidents, visual impairment, and forced relocation for those third parties. For an extensive discussion of externalities see (Sinha and Labi 2007) and Chapter 6 of (de Neufville and Odoni 2003). Externalities may also result for certain individuals from a development that may generally be viewed as a benefit by others. Desirable infrastructure improvements increase property values and thereby rents. A certain number of people however will always be priced out by this development.

Forced stakeholders do not choose to have a stake in the system, but are forced by the decisions of others, such as adjacent communities to transportation facilities.

Stakeholders without decision making power can be either without formal or without any decision making power. Informal decision making power indicates that the outcome of one's influence is unknown, exerted through for example public inquiries and commenting on technical reports. Stakeholders without formal decision making power also exist for space design problems, such as the broader space community, the media, and the interested public. There is however no incentive to specifically incorporate into the design process the interests of stakeholders that neither contribute knowledge, nor funding, nor another valuable resource through which their decision making power would be caused or justified. Stakeholders without formal decision making power in transportation planning have means to influence the planning process but do not know the exact outcome of their actions. Examples for these disruptive actions by stakeholders with informal decision making power are the numerous lawsuits in airport design that typically delay the planning process for years. Even though they may not be able to stop the undesired project, can they impose additional costs on the planners and hurt them in this way. Unfortunately, the dynamic is similar to a war of attrition. Both parties expense time and money on non- value-generating activities. The expense is therefore a deadweight loss: the project continues anyways, but suitors and constructors expensed money and time in court, and the project was delayed. In some cases, transportation constructors preview this expense and therefore offer compensation payments immediately to avoid a lawsuit (Bickenbach, Kumkar et al. 2005).

In other cases, the local public may be seemingly given decision making power through the right to participate in discussions, but they are effectively excluded through less domain knowledge, less money to have studies conducted for their cause and the implicit priority on economic prosperity that is given by many policy makers. Swedish researchers conducted a case study on public participation in the process of Environmental Impact Assessment (EIA) for the construction of an airport. They found that the outcome of a real EIA process was dependent upon what interests were most strongly mobilized. In the case study which they carried out the citizens had very limited opportunity to influence the decision making process. They concluded that the limits to public participation in their case were related to, among others, the consideration as irrelevant of the voices of lay people on environmental impacts, and the implicit priority that the airport planner and the EIA gave to the value of economic prosperity. The authors point out that the short-term goal of economic growth seemed to rule out a more long-term ecological goal of sustainability as well as the democratic goal of broad participation. They conclude that the public were rather excluded than included in the decision making process (Lidskog and Soneryd 2000).

The three kinds of disadvantaged stakeholders are typically not addressed for space systems, and as a consequence have not been addressed in prior MATE applications. Since except for very few exceptions 'powerless' stakeholders do not suffer any negative effects from the deployment of space systems, issues of equity and compensation do not typically arise. Stakeholders for space systems are typically a select set of experts who choose to have a stake in a system because they believe that their benefits outweigh their costs. Since only a select set of experts participate in the design of a space system through contribution of some other valuable resource, they are all vital for the design of the system and have decision making power. It follows that losers and forced stakeholders generally do not exist (some statements in this chapter are strongly generalized for the purpose of caricaturing domain differences and counter examples do exist, such as loser stakeholders who suffer local pollution from launches at NASA's Kennedy Space Center in Florida).

Number and diversity of stakeholders in transportation. Typical stakeholders for space systems include the government, the science community (both academia and government), the aerospace industry, and sometimes commercial customers or international partners. For transportation systems, typical stakeholders include the government at all levels, international government bodies such as the European Union, direct customers (individuals and businesses), private investors, vehicle and system operators, adjacent communities to facilities, enterprises that operate or manufacture vehicles, industries depending on transportation activity (logistics, tourism), and NGOs. The environment, society, and the media are stakeholders in both systems, however with different degrees of interest. It was argued in the previous section that the less specialized capabilities of a transportation system result in a greater 'market size', the market here denoting all people with an interest in the system. This interest can be based on the system's capabilities, externalities, economic, or other impact. For space, the stakeholder set is narrower, since except for a select set of experts, most people are not affected by the quality of the design of space missions in their day-to-day lives.

Negotiation and preference aggregation harder with more stakeholder groups. The larger number of stakeholders in transportation makes negotiation and aggregation of preferences more difficult. There are both theoretical and practical problems with the tracking of utility of large groups. Arrow (1963) shows that there is no theoretically 'good' way to aggregate the preferences of a group, so that an imperfect aggregation mode needs to be chosen. Three neighborhoods may be each severely impacted by only one of the following as a consequence of a highway: noise, visual impairment, and increased traffic through the neighborhood. Problems with preference aggregation and rank ordering may easily be inferred from this situation. Practical problems of preference elicitation include the choice of an expert representative for a group, for example for multiple government agencies, and the preference assessment of large population groups through polls and surveys. These common practices exhibit difficulties in representativeness and impartiality.

Stakeholder determination and salience decision problem in transportation. Since there are typically more stakeholders with formal or informal decision making power than can be treated in an analytic decision and design method, the most important stakeholders need to be identified (stakeholder salience problem). Stakeholders are discussed in more detail in section 2.2.3 in Chapter 2. The ability of 'losers' to disrupt a system shows that a transportation system's performance depends on a basic confidence of all important stakeholders in the system, including those with no formal power.

Table 3-3: *Comparison of "Stakeholders"*

Stakeholder factors	Space	Transportation
Forced stakeholders	Not addressed	Addressed
Stakeholder groups with important informal power	Not addressed	Addressed (informal power through destructive actions)
'Losers' (only risk, no value)	Existing, but downplayed	Addressed
'Market size'	Limited to experts	Very large

3.3 System concepts

A concept is defined as a mapping of function to form (Ross 2003). Although the emphasis in space applications is on vehicle design (Larson and Wertz 1992), a concept can include both physical design and design of operations. It appears from (Taylor 2007) and (Sussman 2000) that the emphasis is on the dual aspects of operations and vehicle design in the conception of transportation systems. Concepts for space systems include swarms of satellites, single monolithic spacecraft, fractionated spacecraft, ballistic spacecraft, and satellite constellations, among others. System concepts for transportation in terms of different ways to achieve an objective can be as broad as the general choice of a transportation mode among air, rail, road, and waterway, or as narrow as a the choice of a corridor for the same mode, depending on the (explicit or tacit) mission objective. It needs to be noted that given the strong presence of legacy infrastructure in transportation system design, the mindset of approaching problems is often the desire to move away from shortcomings in the existing system. The driving question is one of how to fix problems, rather than accomplish a mission which could not previously be accomplished. The latter mindset is typical for design from scratch, which is more prevalent in space systems design. Example attributes that transportation stakeholders are interested in include capacity, accessibility, cost, quantifiable or otherwise rankable measures for externalities, risk to the surrounding population, and the possibility of expanding or changing the use of facilities. More specific problems, for example the configuration of terminals or stations, have their specific attributes. Example Attributes that space systems stakeholders are interested in include speed and resolution of data transmission, altitude, signal peak transmit power, constellation design, cost, survivability and flexibility. Four considerations that are particularly important for the development of a transportation systems concepts are addressed in this section: inheritance, dispersed control, compensation, and different types of cost.

3.3.1 Inheritance

Since in the 21st century transportation systems are practically never designed from scratch, the designer will often be constrained by previously developed vehicles and infrastructure. *Inheritance* is the physical object or conceptual or behavioral artifact that is received from a former system. From a holistic socio-technical perspective, inheritance includes not only physical objects ('hard inheritance'), but also the embedding context in which the transportation facility operates ('soft inheritance'). In an expansion or capital improvement project the existing facilities are a clearly visible artifact of inheritance that the designer needs to take into account. Not only physical facilities are inherited, so too are 'soft' factors such as customers' expectations of certain levels and standards of service, connections to other transportation services, access to different modes of transportation, operational patterns, and generally social norms and expectations of what service a transportation facility should provide. Pieces of infrastructure are further designed with a picture in mind of the existing infrastructure system that they will be operating in and the vehicles they will be serving (even if both are changing). Inheritance can either be a constraint (unchangeable standards), or it can set a baseline that can be altered for a price (access to transportation from other modes). As an example, existing trains can be replaced, and schedules can be changed, but the disposal costs for old trains and the passengers' need to rely on connections to other transportation systems may affect the performance of a concept with inherited components.

While physical system and expectation inheritance do play a large role for space systems as well, this issue is not often discussed in the space system literature and the existence of inheritance has not been addressed in the MATE process yet. According to the pedagogy of graduate space system design courses, clean sheet design has a strong appeal and often overrides discussions of "messy" inheritance.

In a MATE analysis inheritance could be modeled as a hard constraint (physical location of additional facilities), or in the form of minimally acceptable attributes (maximum walking time for passengers). Another possibility is to not model the inherited features at all and individually check candidate designs for consistency. The latter procedures may not be efficient depending on the amount of additional work. Since inheritance can be changed however, e.g. reducing walking distances in stations or terminals through people movers, additional checks are needed in the first case in which inheritance is modeled as a hard constraint.

3.3.2 Control situation of system components

Concurrent design requires a designer to exercise control, the authority to change, over a system in order to impose his design choices on the components. An "optimal" design for any system is of little help if the political and social environment impedes its realization. For US space systems, a situation of complete control or control dispersed over a relatively small number of stakeholders is a reasonable assumption. Without control at a level of dispersion that allows negotiation a spacecraft will not realistically be built. NASA and the US Air Force are often single decision makers over the vehicles they own. Occasionally multi-service satellites (e.g. Navy, Air Force, etc.) are under joint control. For transportation systems, control situations vary widely. Typically different pieces of transportation infrastructure and vehicles are owned by different entities and potentially operated by a third party, dispersing control widely. For road traffic, government or private investors own roads, bridges, and tunnels and navigate traffic on them, whereas trucking companies and individuals own and operate the vehicles. Since the control of the roads and control of the vehicles reside in different stakeholders, concurrent design of a system encompassing both is difficult due to the dispersed decision making power, for instance for a trucking company operating on public roads.

Dispersed control also plays an important role for space systems, even though the dispersion is not as extreme as in airports. Chattopadhyay (2009) suggests a method based on MATE, SoSTEM, to be applied to Systems of Systems (SoS), taking into account their differences from traditional systems. In considering transportation systems, we are in fact often looking at SoS due to the frequently encountered dispersion of control. Issues in applying MATE to the transportation domain therefore stem both from domain differences to the space domain, and from the fact that transportation system are naturally interconnected systems and fundamental changes almost always have influences on the SoS level, the level of interconnectedness of different individual systems (even though we may choose to ignore this perspective depending on the scope of the analysis).

3.3.3 Monetary parameters as part of the design

Compensation for 'losers' for transportation systems is one way to achieve a redistribution of costs and benefits that is more desired by a decision maker, typically a government body. Unequal distribution of costs and benefits is a problem not unique to transportation systems, but unlike for space systems, it is treated in the transportation literature. In theory, an imbalance in the distribution of risks and benefits can be restored through an interpersonal redistribution of benefits and cost, meaning a monetary compensation for those who bear the costs or risks. The topic of redistribution of benefits is a controversial one since it requires an interpersonal comparison of utility (i.e., how much satisfaction of person A should be traded for how much satisfaction of person B, and on what basis are those levels of satisfaction compared?). Bickenbach (2005) points out how in Germany the redistribution of costs and benefits is hindered by technical restrictions and information problems. While compensation seems fair and desirable, the actual identification of impacted residents, the degree of the impact, and of the inconvenience caused through the impact, is difficult to assess. Asking residents provides an incentive for them to overestimate the level of impact to receive a higher compensation. Different individuals will value silence or the financial compensation differently, making the valuation of the utility of compensation highly dependent on who is asked. Grayling (2001) claims that aviation does not pay its full social and environmental cost, which means that not all externalities imposed are incorporated in the fares and prices paid by those who use aviation infrastructure. The consequence is that ultimately another body has to pay for externalities caused by others, or that social and environmental compensation does not occur in full or does not occur at all.

Another example for monetary parameters as part of system design is the distribution of costs. For transportation, different bodies co-finance projects. Financing bodies in the examples later on are the European Union, a Private Investor, the country of Portugal, the City of Chicago, the state-owned Chicago Transit Authority, and a Private Operator who owes a concession payment. Cost shares are important design variables to reflect a situation of co-financing.

Non-monetary design parameters mean that design variables needs to be expanded to include design factors that affect user preferences for a concept and the cost of a concept in the same way as other design variables, but are not naturally related to the physical system.

3.3.4 Accounting for different types of cost

The existence of externalities reveals that there are negative impacts incurred and imposed by transportation systems that are of a different type than monetary costs, such as social and environmental "costs". Different types of costs are in the following referred to as "expenses". In several decision methods, such as the one proposed in (Min, Melachrinoudis et al. 1997) for the airport location problem, or generally in CBA, non-monetary expenses are often converted to monetary costs according to the level of compensation that needs to be paid to the sufferers of such expenses. This approach is practical for some applications, but less so for situations in which a decision about the impact and inconvenience of externalities cannot easily be made up front, in which different impacts need to be weighted or traded-off against each other. In past applications MATE accounted only for the treatment of monetary cost. Space systems do produce externalities in the form of waste and debris in space, however, these effects have largely been secondary and are typically not an issue of concern during design. Given the importance of externalities in transportation design problems, the reflection of different cost types, such as monetary, social and environmental cost is important. Van Eeten (2001) and Schmidt (2005) provide examples for situations in which environmental effects, and effects on quality of life, as a result of transportation systems have very high priority to certain stakeholders.

Table 3-4: *Comparison of "System concepts"*

Concept factors	Space	Transportation
Understanding of concept	Mainly physical	Physical and operational
Inheritance	'Soft inheritance' plays important role, but typically not addressed	Common issue, addressed
Control over system	Central or dispersed among few decision makers who negotiate and co-design system	Dispersed to varying degrees, co-design not always possible
Non-monetary design parameters	Not addressed	Compensation and cost shares common issues, addressed
Types of cost	Monetary	Multiple types of cost (monetary, environmental, other)

3.4 Constraints

Constraints are unchangeable factors of any kind that place limits on what is possible in the design process. Some constraints are obvious at the beginning of the design process, such as the laws of physics and legal constraints. It is important to have a broad view on the system to also consider less obvious constraints, such as human capabilities, to ensure the validity of the later analysis. Differences between space and transportation result from the embedded nature of transportation systems in various other systems and the often geographically removed nature of space systems. An important issue confronting space systems is its need to operate in harsh environments, which has made design for robustness and survivability high priorities. Unlike space systems, transportation is typically embedded in or at least held to similar standards of resource-efficiency or profitability as a pure market environment with its pressure, even though a large number of transportation systems rely on governmental subsidies. The level of competition varies substantially, from very high (airlines) to very little for natural monopolies (some airports and rural roads). All transportation systems are expected to meet the social norms of reliability and timeliness, which implicate the need to deal fast with disruptions.

Table 3-5: *Comparison of "Exogenous factors"*

Exogenous factors	Space	Transportation
Laws of physics, technological constraints	Important (especially orbital dynamics, energy required to get there)	Play minor role, mainly operational and practical constraints
Maintenance	Difficult due to remoteness	Key consideration in operation
Inherited infrastructure	Existent, but downplayed	Key consideration in design
Dual use (military-civil), and other restricted technology	Adds a lot of regulations, restrictions on technology transfer	Plays minor role, mainly civil use, technology less sensitive apart from some aviation technology
Safety	Protection of national safety important	National safety an issue in border protection, but emphasis on personal safety of passengers
Market environment	Low, but pressure to be resource-efficient increasing	Increasing, pressure to be profitable/ resource -efficient and to use standards similar to private sector businesses
Social norms on performance	Survivability, robustness, no failure	Reliability, timeliness
Regulation	High, goal to protect national safety	Some regulations, goals mainly to standardize passenger safety and promote connectivity
Environmental constraints, land-use	Less important	Important
Impact of investment structure on design	Sunk costs of development, fixed launch costs	Discrete, bulky increase in capacity, slow repayment of high initial investment

As space system design moves more towards the development of an on-orbit infrastructure ((Long, Richards et al.; Joppin and Hastings 2006; Richards 2006; Nilchiani and Hastings 2007)), these systems will begin to take on characteristics similar to those found for transportation systems, such as constraints by environmental externalities. Table 3-5 gives an overview over the context in which space and transportation systems are designed. Similar constraints, like the laws of physics or issues brought about by high fixed costs, are very powerful since they suggest invariants in system design that need to be considered independent of domains.

3.5 Dynamic Lifecycle Issues

Definition of the end of system life. Definition of the end of system life. The lifecycles, meaning the useful lives, of transportation systems, are highly variable. Systems that require high investments typically have a lifecycle of decades, such as trains, rails, roads, airports, and airplanes. What are commonly regarded as lifecycles for these systems are mainly approximations, for reasons of lack of data and controversy as to the end of a system's life. The end of a system's life is a question of definition, as it can be defined, for example, as the point of absolute failure, the failure to meet certain technical standards, or economic inefficiency due to too high maintenance costs (de Neufville 2007). In many cases the transportation system keeps running while components are being replaced, so that the lifecycle of "the system" is in fact a sequence of several generations of physical systems. Road pavements are commonly regarded to have a lifecycle of 17-27 years, depending on the used material (de Neufville 2007). The transportation system that involves the roads however keeps functioning while single roads are being repaved, through narrowing of roads or redirection. In the automotive industry, 'lifecycle management' serves to satisfy the customer. New generations of luxury vehicles are released after a number of years that is well-researched by marketers. This point in time allows the customers of expensive cars to drive the latest model until the majority is ready for the purchase of a model of the next generation. Due to remoteness, inability to repair or upgrade, and high cost for development, space systems are typically built for 10-15 year lifetimes. The lifecycle of a system indicates how often systems are going to change. Even though the nature of change may be uncertain, the knowledge of when change is expected is vital for the development and evaluation of system concepts.

Table 3-6: *Comparison of "Dynamic Lifecycle Issues"*

Lifecycle factors	Space	Transportation
Definition of the end of a system's life	Typically operational end of life, or end of mission	Varying, disposal problematic, system exists while components are being replaced
Lifecycle	10-15 years	Varying, in the range of decades
Changing contexts	Important	Important

Changing contexts. Changing contexts impact user preferences and the perceived success of a system. Since the design and deployment of space and transportation systems is typically in the range of decades, these systems are likely to operate in multiple contexts. Examples for significant changes include rising priority of safety in air transportation after 9/11, and the emphasis on environmental efficiency and sustainability of fuel sources for transportation in general. An example for a changing system context for space is the evolution of a political context from one dealing with a monolithic, well-funded adversary, to one with diffuse threats and rapidly changing technology. In this situation, efficient use of scarce resources plays an increasingly important role which is similar to transportation. The paradigm of operationally responsive space (Viscito 2009) indicates a priority shift from classic (legacy) design to incorporate as many payloads as feasible to a new design of shortened schedules and hopefully lower budgets. While classic ('big space') design is performance driven, operationally responsive space is schedule driven. Operationally responsive spacecraft become desirable when a new capability is needed or there is a loss of legacy systems (Richards, Viscito et al. 2008).

Due to the long lifecycle and long design phase in both space and some transportation systems, the consideration of changing contexts and user preferences is crucial for sustained system performance for both domains. The need for changeable designs in space systems, and for a theory to help plan and implement infrastructure transformation, respectively, is pointed out by members of both communities (Hansman, Magee et al. 2006; Ross 2006).

Chapter 4 Case Study 1: Chicago Airport Express

4.1 Approach

The case study consists of 12 parts: (1) a description of the approach, (2) an introduction, (3) identification of stakeholders and (4) elicitation of their attributes using both CBA and MATE, (5) generation of alternative system concepts, (6) calculation of Cost-Benefit Values for different options, (7) calculation of aggregated Utility-Expense and plot of tradespaces for different options, (8) tradespace exploration, (9) evaluation of the best design option, and (10) discussion of the shortcomings of CBA that were mentioned in the literature review in Chapter 2. Chapter 4 concludes with a discussion of (11) political feasibility and potential opposition, revealing unarticulated values, and (12) technical recommendations. The MATE and CBA studies in this chapter are based on real data to the extent possible. In cases for which no real data was available, the calculations are based on assumptions by the author. The studies in this chapter are intended to illustrate decision making methods and do not reflect the official view of any of the involved agencies, nor are they intended to provide technical guidance.

4.2 Introduction

Chicago's main airport, O'Hare International, is currently accessible via two main routes: by road via the Kennedy Expressway, and by train via the Blue Line, a rapid transit line operated by the Chicago Transit Authority (CTA) (Figure 4-1). The Kennedy Expressway is one of the main arteries into Chicago and serves commuters as well as travelers to the airport. The Blue Line consists of two tracks and operates at 5-10 minute headways depending on the time of day. Headway is a common metric at transit agencies for the frequency of vehicles and measures the time between vehicles.

Both public transit and individual travel (car, taxi) are unsatisfying for airport travelers. Access to the airport by bus, hotel shuttles, taxis or car drop-off is unreliable due to the Expressway's frequent and highly variant congestion (Figure 4-2).

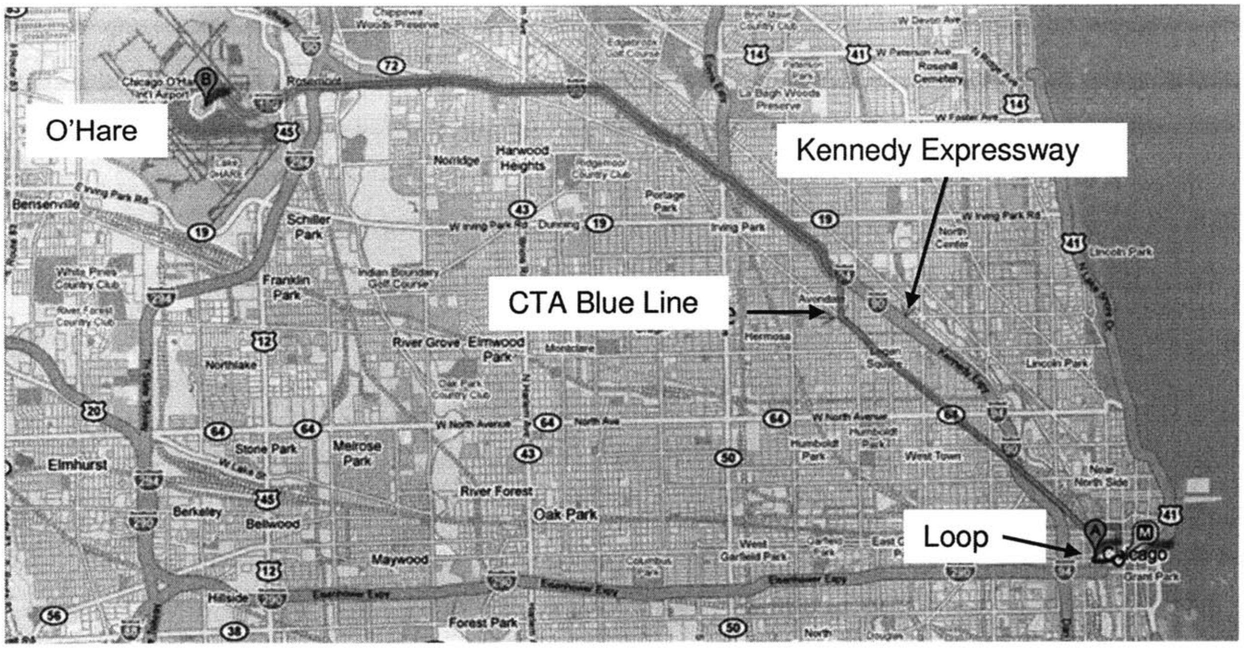

Figure 4-1*: Airport access via Kennedy Expressway and CTA Blue (Google Maps 2009)*[9]

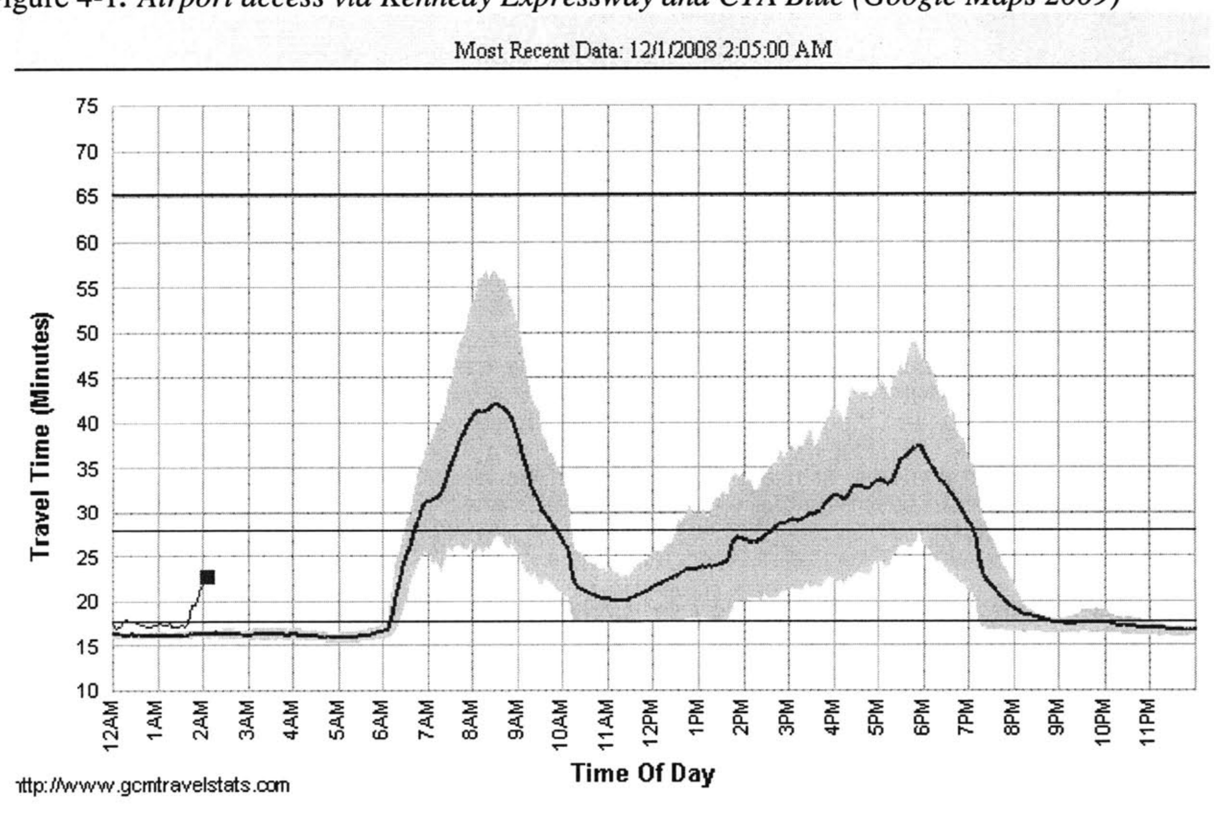

Figure 4-2: *Travel time and 1σ-range on Kennedy Expressway (GCM Travel Statistics 2008)*[10]

[9] Retrieved 12/27/2009, from http//maps.google.com

[10] Retrieved 12/07/2008, from http://www.gcmtravelstats.com/Default.aspx?selLinks1=24

Travel times range from as short as 25 minutes to over one hour for the 16-mile trip from the Loop (downtown Chicago) to the airport. The CTA Blue Line, on the other hand, stops 15 times on its way from the Loop to O'Hare. The ride takes 50 minutes from downtown and is strenuous for travelers with luggage: a number of train stations are not equipped with elevators, the turnstiles are hard to pass with luggage, and the train does not provide storage space for large pieces of luggage.

The system boundary of the planned airport express encompasses the physical connection between a dedicated downtown terminal (currently under construction) and the CTA terminal at O'Hare, the tracks and rolling stock, and existing local connections from downtown to O'Hare (the Kennedy Expressway and the CTA Blue Line). On the operational front, the system encompasses basic operational parameters: frequency of the service, travel time and price.

4.3 Identify system needs and stakeholder groups

Anecdotally, it has long been realized by travelers as well as planners at the CTA and in the Office of the Mayor of Chicago that there is currently no good way to access the airport. Several studies have been carried out since 1998 with the goal of identifying a feasible design solution. The proposals to date focus exclusively on technically acceptable, but expensive, non-stop rail connections. Until the present day (August 2009) no plans have materialized due to a lack of funding.

To ensure Chicago's competitiveness with other global cities for conferences and business, a fast and reliable airport connection is needed since O'Hare is located somewhat remotely from the city center. A mission has not been formulated in the planning documents in the form of a clear statement of intent of the goal that the system should achieve. It appears that two assumptions underlie all of the planning documents: 1) that an airport express is a priority, and 2) that Chicago would greatly benefit from having such an express. During interviews with partners representing system stakeholders, the closest to a *mission statement* that interviewees seemed to agree on was "to improve access from downtown Chicago to O'Hare International Airport, whereby improved accessibility must include reduced travel time (compared to the status quo)." This mission was not formulated by any one of the interviewed stakeholders, but was the result of individual discussions about a mission statement. The preceding direct question about the mission or goal of the project could not be answered by the interviewees.

The main *decision making stakeholders* are those that are expected to contribute to the funding of the airport express: the City of Chicago, the CTA, and a Private Operator. In addition, the affected public and travelers to the airport have a stake but no formal decision making power. A design selection is a prerequisite for the extensive studies that have to be conducted as part of an application to a Federal Grant program such as "New Starts". Since the strategic decision about whether or not to invest in studies for an application for federal funding is excluded from the decision problem, a preference for a design that could be self-financed is assumed.

The *City of Chicago* hopes to sustain economic growth in the downtown area and to ensure Chicago's competitiveness with other world cities for business and conferences. The *CTA* as the operator of Chicago's public transportation system would play an important role during the construction and operation of the proposed airport express. Due to existing maintenance facilities in close proximity, a trained workforce and general expertise, the operation and maintenance of the airport express would be outsourced to the CTA. The main clientele in need of better accessibility, explicitly stated or implied, are business travelers. Based on the interviews, there seems to be a common understanding between the CTA and the City of Chicago that the airport express would need to be a premium service in order to attract the (presumably price-insensitive) business segment of the market. Since the CTA does not have experience with running a premium service, a private sector concessionaire (*Private Operator*) was suggested to be charged with the management of the airport express (Parsons Brinckerhoff Consult Inc. 2006). The hope is to leverage business knowledge from the private sector, secure a contribution to the project funding through availability payments, and help establish a new premium brand name.

Other stakeholders without formal decision making power include *passengers to O'Hare*, segmented into *business* and *leisure*, *residents adjacent to tracks*, and the *greater Chicago public* (the "taxpayer"). *O'Hare International Airport* and to a lesser degree some *airlines* are further stakeholders. O'Hare and airlines have been excluded from the City's technical studies with no reason given. It appears that the planners at the Mayor's office and the CTA do not count on funding from the airport and therefore do not pay them much attention. An agreement with O'Hare is mentioned stating that the CTA may modify its O'Hare terminal to accommodate an airport express (WilburSmith Associates 2004).

4.4 **Identify attributes of interest for each stakeholder (group)**

Attributes are the decision criteria used for assessing the goodness of each alternative being evaluated. Attributes are elicited in different ways for MATE and CBA.

4.4.1 Attribute elicitation in CBA

In CBA, guidelines are typically consulted for costs and benefits to be considered in a project. An FHA primer (FHA 2006) and guidelines on the website of the California Department of Transportation (California Department of Transportation) were used for this case study to define costs and benefits for the Airport Express project (Table 4-1).

Attributes for CBA are often qualified as benefits or costs depending on their change *relative* to the status quo (hard and soft inheritance). A reduction in undesirable attributes such as emissions, accident rate, noise, or pollution is a benefit, whereas an increase in these attributes would constitute a cost. Equally, increases in employment or property value are benefits, but decreases compared to the base case (roughly equivalent to the status quo) constitute costs. The difference between the base case and status quo is explained in section 4.6. Construction cost, maintenance cost and operating cost of new infrastructure are assessed without comparison to the base case, unless the new infrastructure replaces old infrastructure that would no longer be operated (in which case the cost for operating the old infrastructure is saved from then on).

The categorization of attributes as costs and benefits in Table 4-1 is based on *expected* increases and decreases in attributes. However, if it turns out that for example emissions are increased for a design option, and not reduced as expected, the attribute would be reassigned to the cost column. The FHA primer states that *change in operating costs for vehicles* tends to constitute a minor share of the benefits of a project. *Reduction in crash rates* is a less important concern given the goals of the project of improving accessibility to O'Hare. Both attributes were therefore omitted from the CBA.

Table 4-1: *Relevant costs and benefits for Airport Express project*

Benefits	Costs
First order effects	
Travel time savings	Construction cost
- To Airport travelers	Operating cost
- To Blue Line riders	Delays to Blue Line passengers
- To drivers (congestion relief on Kennedy)	Delays to drivers on Kennedy Expressway
Emission reduction	Noise to residents
	Adverse neighborhood impacts from construction
Second order effects	
Long-term job generation	Job losses (from changes in operation at CTA, cab drivers)
Short-term job generation (construction)	Loss of property value in neighborhoods impacted by noise
Attraction of businesses and new development	
Increase in property value around downtown terminal	

In line with recommendations in the cited FHA primer, second order effects are not quantified. It is important to bear in mind that transitions from the status quo create transaction costs. An example for first order effects is change in noise impact. If a certain level of noise was impacting Neighborhood A previously and is now, to the exact same extent, impacting Neighborhood B (whereas Neighborhood A is now enjoying silence), from the point of view of a CBA analysis, nothing has changed even though a transfer of externalities has occurred from Neighborhood A to Neighborhood B. From CBA point of view, there is no reason either situation would be preferable. Realistically however, the transfer would result in transaction costs including, at a minimum, the required communication to convey to the public the rationale for the change, and to appease the newly impacted residents to some extent. Those transaction costs are generally not considered in a CBA.

The example of job gains and losses makes the point even more drastic. If 100 jobs are lost and 100 new ones created, the job losses will likely cause considerable protest among those who lose them. Taking something away from people (e.g., silence, or a job) will always cause a commotion because people feel that they have a right to the status quo.

As a brief aside, to better understand how costs and benefits are perceived by decision makers in a change from the status quo, Prospect Theory (Kahnemann and Tversky 1979) can be used to help explain the issue by illustrating that people are very loss averse, preferring to stick to the status quo. Kahneman and Tversky (1979) observed that people do not make decisions based on the absolute level of an outcome, but rather in terms of gains or losses. Prospect Theory is a descriptive theory in that it attempts to explain how decisions are actually made through empirical observations and extrapolation. Kahneman and Tversky identified four biases in how people actually make decisions:

1) People make decisions based on *changes* of "wealth," not the absolute level.
2) People are loss averse. People weight a loss of $100 about twice as much as a gain of $100. In terms of jobs (under the simple assumption of equal happiness), 20 new jobs would need to be created to offset the loss of 10 jobs.
3) People are risk seeking in the loss domain and risk averse in the gain domain.
4) People subjectively interpret probabilities.

It is for this subjectively different perception of losses and gains that job losses and gains are listed separately in the benefit and cost column. The result to society of 100 people losing their jobs along with 101 people gaining jobs is not the same as the net creation of 1 job. Prospect Theory suggests that this is true for other metrics as well, including dollars.

When deciding whether to use Utility Theory (prescriptive) or Prospect Theory (descriptive) to guide decisions, Ross (2003) cites Harvard Economics Professor David Laibson as arguing, in his Psychology and Economics course, that over the course of multiple decisions, the [prescriptive expected] Utility Theory will make people better off than the descriptive Prospect Theory since it removes biases. However, even if MAUT leads to superior decisions in the long run, as suggested, humans' subjective perception of a single decision is an important issue in public policy, and needs to be addressed in the justification of a decision. This thought will be further discussed in the section on political feasibility of design options (4.11).

4.4.2 Attribute elicitation in MATE

In MATE, an attribute denotes any cost or benefit, tangible or intangible, that a stakeholder is interested in (so long as the set of attributes is complete, decomposable, operational, non-redundant, minimal, and ideally perceived independent, as discussed in section 2.1.4.1). The MATE attributes for this case study were elicited in interviews by asking stakeholders the question "What do you hope to get out of the airport express?" To identify acceptable ranges, the question was asked "What level of a specific attribute would cause you to reject an alternative based on this attribute alone?" (step-out condition) for a utility of 0. For a utility of 1 the question asked was "What level of a specific attribute would completely meet your expectations?" Usually, more explication was needed to clarify that this level should be the lowest possible level for which a stakeholder was "practically completely satisfied", and that it did not need to be the lowest possible level of an attribute (such as a cost of 0 or a travel time of 0). There is some imprecision in formulating the question in terms of "practically completely satisfied", but it helped the stakeholder to think about a satiation point, especially with regard to attributes that a stakeholder wants to keep at low levels. Theoretically, a satiation point for goods exists in most cases. At the satiation point more of a certain attribute (or less, depending on the direction) does only provide marginally more utility, or no additional utility at all. In the case of monetary cost, it appeared in the interviews that the satiation point is at extremely low levels, if it exists at all (point after which a stakeholder does not care anymore about spending one dollar less on a project).

Since the time for the interviews did not allow for a structured utility interview, only the minimally (x_{iMin}) and maximally (x_{iMax}) acceptable levels of an attribute were elicited. A power-function $U(x)= x^{-\gamma}$ is assumed to underlie the utility function. For $U(x)= x^{-\gamma}$ returns are diminishing, for $U(x)= x / [x^{-0}(x_{iMax} - x_{iMin})]$ the function is linear, and for $U(x)= 1-x^{-\gamma}$ returns are increasing (Figure 4-3). Since the shapes for utility curves were not elicited in the limited interview time, varying the utility curves would allow sensitivity of the tradespace to the shapes of utility functions to be explored.

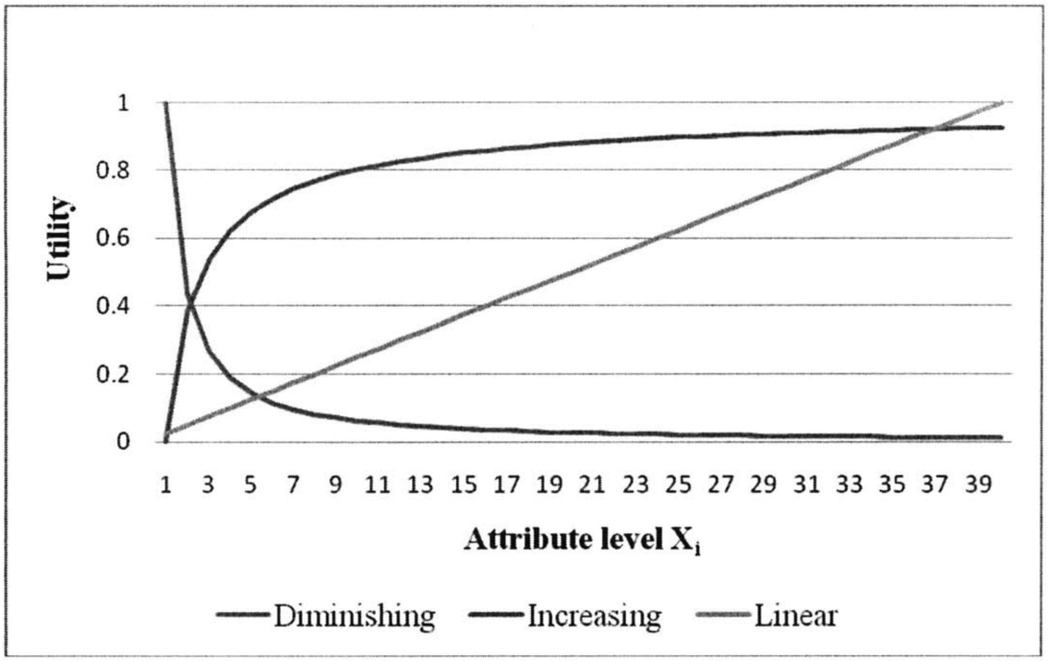

Figure 4-3: *Some basic shapes of utility functions used in the case study*

The Private Operator was able to express a level of an attribute that he would "expect" to see. This information is included in the appropriate table to allow a comparison of how far the levels for a utility value of 1 and 0 depart from this expected value. For consistent treatment of the three stakeholders, the information is not included in the later calculations.

Interviews with proxies for the three main decision making (Interview partners 2008) were conducted in July and August of 2008 in two one-hour long telephone conversations with each proxy. The interview partner representing the City of Chicago was a planner at the Mayor's Office who had been involved in the planning for the airport express since 2000. A General Manager at the CTA who has been involved with the airport express since 2006 represented the CTA. A consultant from Parsons Brinckerhoff Consult Inc. who participated in an Airport Express business plan study (Parsons Brinckerhoff Consult Inc. 2006) assumed the role of the Private Operator.

Attributes were elicited by asking the proxy stakeholders the open ended question of what they were hoping to get out of the airport express. All stakeholders were encouraged to think about additional attributes until a number of 8-10 had been suggested. A second question inquired about quantifiable metrics for these attributes, and a third question elicited acceptable ranges.

Lastly, in order to assess the tradeoff among attributes, stakeholders were asked to distribute 100 points over the attributes, representing the importance of each. The interview process employed here sought to elicit the most important information to build a MATE analysis using limited interview time (2 hrs per person), including time to explain the purpose of the interview and clarify questions. The employed process was not as rigorous as the one suggested by formal MATE. Several hours per decision maker needs to be budgeted to perform a structured utility interview, including the elicitation of each single-attribute utility curve, the eliciting of k_i values, and validation of the utility models. The recommended interview process is explained in more detail below. An advantage of the informal interview method used for the interviews for this case study was that the interviewees shared many of their experiences with the airport express project. This knowledge helped the author, whose public transportation experience is limited to two years in graduate school and a 3-month internship at the Chicago Transit Authority, to understand practical issues in the planning of the airport express. Due to the informal method employed for the interviews, a number of issues were possibly introduced, which would have been mitigated using a more rigorous utility elicitation process.

1) A constraint on stakeholders to distribute 100 points among all attributes forced them to trade-off the importance of different attributes in their heads. This process hides information about the intensity which stakeholders feel about different attributes, especially when considered together. The weights are only meaningful for ranking attributes against each other, but give no information about the utility that a decision makers derives from one individual attribute (e.g., at maximum level with all other attributes at X_{iMin}) towards multi-attribute utility. Analytically, the k_i values add up to 1 and the generalized Keeney-Raiffa function is forced to reduce to the simple linear weighted sum function for multi-attribute utility:

   $U(X)=\sum_{i=1}^{n} k_i \, U_i(X)$ for K=1

2) Information about cross-reactions of attributes (complementarities) was not made explicit during the interview process. This is a general shortcoming of the linear weighted sum multi-attribute utility function.
3) Preferential and utility independence of attributes was not discussed with the interviewees. *Preferential independence* means that the order between any two levels of

an attribute is independent of the level of any other attribute. This axiom makes possible the comparison of two dimensions (two different attributes) at the same time, independently of other attributes. Preferential independence is a prerequisite for the use of the lottery equivalent probability approach for attribute elicitation that is described in (de Neufville 1990). *Utility independence* denotes that the relative intensity of value k_i for different levels of one type of attribute is independent of the level of all other attributes.

Ross (2003) the following guidance on how to conduct a utility interview and craft a multi-attribute utility function.

> MAUT allows for the aggregation of single attribute utility functions into a single metric that takes into account preferences on tradeoffs between the attributes and can be used as a driver for tradespace exploration. [...] Once the attribute definitions and ranges have been decided, the utility interview can be written. The interview process that is currently recommended is taught in De Neufville's *Applied Systems Analysis.* The entire interview is a collection of single attribute utility interviews and a corner point interview. The single attribute utility interviews use the lottery equivalent probability method and each question is dependent upon the interviewee's responses. The utility function for each attribute can be derived from the indifference points from the interview. It is important to carefully craft the scenario for each attribute to place the interviewee in the proper mindset to answer lottery questions for the attributes. (Thinking in terms of probabilities is difficult and is a major limitation of the process. It is important to guide the interviewee until the person is comfortable with the question format.)
>
> The attributes for the User [generally: interviewee] must be finalized before the interview can be conducted, though iteration of the interview is possible and greatly facilitated by computer-based interviewing. It is highly recommended to peruse the literature on the issues involved in utility interviewing as it is inherently a social science experiment and therefore may be outside of the normal experience base of an engineer.
>
> Verification of the MAUT assumptions regarding utility and preferential independence of the attributes allows for the use of MAU functions. If verification fails, it will be necessary to redefine the attributes, or the simple multiplicative form of the MAU function will be invalid. It is possible to relax the assumptions of MAUT, however it is recommended that any designers considering such a strategy read Keeney and Raiffa's *Decisions with Multiple Objectives* in order to fully understand MAUT. Validation output is the confirmation that the utility functions adequately represent the User's preferences. Communication of these functions increases both the confidence of the designers and the User [generally: interviewee] as well. (Often a decision maker may feel uncomfortable being represented by a simplistic proxy function; emphasis on the communication aspect of the function may alleviate some of this anxiety.)
>
> (Ross 2003)

Validation has to happen through a conversation with the interviewee. The goal is to check if the interviewee feels that his preferences are adequately captured by the function. This can be done by showing the utility function to the interviewee, or by asking him to rank certain design options and see if the function gives the same ranking result.

4.4.2.1 MATE Attributes for the City of Chicago

Table 4-2 to Table 4-4 in this section summarize the results of the interviews and give an idea of the position of each stakeholder. The tables contain the following information about each attribute:

Weight: Assigned number of points from a total of 100 designating the relative importance of each attribute (normalized to add up to 1 in table) to the stakeholder who suggested it

Attribute: Specific characteristic of the airport express that a stakeholder values

Measure: A quantifiable metric to assess the level of each attribute

X_{iMin}: Minimally acceptable level of the attribute (utility=0). Below the minimum level the stakeholder will abandon the project based on this attribute alone.

X_{iMax}: Denotes the level above which an additional increment of the attribute would not contribute to increased satisfaction (utility=1).

Table 4-2*: City of Chicago attributes (Interview partners 2008)*

Weight $\Sigma = 1$	**Attribute**	**Measure**	**X_{iMin} (u=0)**	**X_{iMax} (u=1)**
0.12	Estimated Chicago tax base change	Increase equalized assessed value of property downtown	3-4% inflation adjusted	10%
0.12	Generation of Employment	Number of jobs created (short-term/ long-term)	300/ 20,000	1000/ 100,000
0.12	Availability of outside project funding	Local share requirement	50%	0
0.1	Attraction of passengers (visitors) to Chicago (city)	Ridership daily on airport express	4,000	25,000
0.1	Equity	Investment compared to investment in regular transit system (annual share in capital budget, annualized over 15 yrs)	25%	10%
0.08	Estimated out-of-town	Hotel room occupancy	80%	95%

	visitors to Chicago			
0.06	Travel time	Min	30 min	12 min
0.06	Reliability	Schedule deviation	20%	0%
0.06	Attraction of businesses to downtown	Square footage of new development from project	+ $1M increase in excess of annual trend line	+ $10M increase
0.06	Initial public support	Percentage favorable	40%	70%
0.06	Confidence in final project cost	% confidence	75%	100%
0.06	Confidence in final project schedule	% confidence	75%	100%

4.4.2.2 MATE Attributes for the CTA

Table 4-3*: CTA attributes (Interview partners 2008)*

Weight $\Sigma = 1$	**Attribute**	**Measure**	**X_{iMin} (u=0)**	**X_{iMax} (u=1)**
0.2	Up front investment from CTA	$M	100	0
0.2	Impact on current operations - overall capacity	% of capacity needed for airport express	25%	0%
0.2	- probability of recurring delays to existing trains	%	5%	0%
0.1	Degree of certainty about project cost	Variance of cost share at CTA's responsibility	+10%	0%
0.09	Maintainability 1	Hrs of day available for maintenance	0	6
0.05	Maintainability 2	km of shared track	All shared	0
0.05	Availability- Prevention	Failures per month	15	0
0.05	Availability- Recovery	% of trains under repair	20%	0%
0.02	Dispersion of control	# of actors involved	4	1
0.02	Market share	% of airport travelers	4%	50%
0.02	Length of concession contract	Years	50	1

Impact on current operations refers to expected delays on the current local service on the Blue Line (also called "local service"), in cases in which tracks may be shared with the airport express. *Availability* means the ability of vehicles to be ready and able for use, and is a result of preventing or quickly fixing problems if they do occur. Dispatching a train in insufficient state or decommissioning from service results in delays and annoyance of passengers. The ability to prevent this kind of failure by only dispatching trains that will successfully complete their assigned route is termed availability by the author. The causes for failures can be internal or external. External causes include obstacles on the tracks or destruction of infrastructure by external forces. Internal causes include drivers who show up late or do not show up at all, leading to a bus missing from service, or the inherent probability of a vehicle breaking down (increasing with age), factors which are not influenced by external circumstances.

4.4.2.3 MATE Attributes for Private Operator

Table 4-4*: Private Operator attributes (Interview partners 2008)*

Weight	**Attribute**	**Measure**	**Expected level**	X_{iMin} **(u=0)**	X_{iMax} **(u=1)**
0.40	Return on investment, pre-tax	%	20	12	35
0.125	Freedom of concessionaire to make changes (e.g. raise fares), broad requirements for operation	Scale 1-5 (5 maximal freedom, 1 no freedom)	2	3	1
0.125	Competition agreements (with CTA and City, prohibiting launch of competing services or construction of competing roads)	Scale 1-5 (5 no competition, 1 no agreement)	4	3	5
0.1	Concession payment for right to operate airport express that has: shared tracks with local service/ individual right-of-way (0 if no profits expected)	$M	0/100	60/ *500*	0 */200*
0.05	Length of concession contract	Years	30	20	50
0.05	Fare growth per year	%	3%	2%	6%
	Fare price in year 0	$	$15	$12	$20
0.05	Construction schedule overrun	Overrun in years	0	-0.5	0.5
0.05	Growth of operating cost per year	%	3%	6%	0%
0.05	Ridership growth	%	3%	1%	5%
	Ridership level	# pax/ year	3mn	2.5mn	4mn

Freedom of concessionaire to make changes refers to the influence that the CTA and the City of Chicago would have on service parameters, such as span of service, frequency, and services offered. Such required policy service standards secure a basic welfare level which often is in conflict with the goal of profit generation or at least self-sufficiency. Therefore, public agencies may require private operators to maintain a minimum level of service, maximum annual fare increase, or mandate service to certain areas as part of a concession agreement.

The Private Operator in this case wants to keep those costly constraints to a minimum. As can be seen from the weightings, Return on Investment is by far the most important attribute. In fact, the Private Operator does not care about the fare level per se because the level alone does not provide him with a profit guarantee, rather profit (π) is a function of fare (p) times demand (q) minus (fixed and operating) cost (C) for a time interval.

$$\pi = p*q - C$$

In essence, and the Private Operator stated so, he cares only about profit. When asked about other attributes, he enumerated other factors of the profit equation, but assigned them low weights. The proxy representative pointed out that that any concession payment by the Private Operator would be unrealistic for this project, since realistically no profits are expected based on the low ridership estimates suggested by the CTA. Towards the end of the author's internship at the CTA a financial analyst performed the same calculation and pointed out that participation from a Private Operator could not be expected based on current projections. This result led to some discussion within the CTA. The values that the proxy representative for the Private Operator indicated for concession payments provide an order of magnitude orientation for projects with higher ridership estimates.

Growth of operating costs refers to the contractually agreed upon payments that the Private Operator as concessionaire would owe the CTA in a model in which the CTA would perform the maintenance and operation (but not management and marketing) of the airport express. Any difference between actual operating costs and contractually specified payments would be the CTA's to bear.

All stakeholders, most notably the City of Chicago, have goals of different hierarchical levels. *Broad high-level attributes,* such as employment generation or tax base change, are predominantly dependent upon external factors in addition to factors that are influenced by the Airport Express. Except for major differences between architecture concepts, those attributes cannot adequately distinguish between any two different design concepts. *Mid-level attributes* relate clearly to the Airport Express, but are significantly influenced by external factors in addition to technical ones. They are too broad to be "engineered for", in the understanding of clearly being determined by system-internal technical factors. Ridership growth and construction overrun are examples for attributes that clearly depend on the system (airport express), but are subject to many (often uncertain or uncontrollable) external factors, and can therefore not be controlled or even predicted by the designer. *Low-level attributes* depend solely and in a clear causal relationship on system-internal factors (travel time, fare, availability, maintainability). In addition to attributes that are influenced by the airport express, there are attributes that refer exclusively to negotiations that have to happen between the decision makers. *Contractual attributes* are decoupled from decisions that affect the physical components or operations of the system. They refer to contractual agreements between the stakeholders. Especially the Private Operator expressed a strong interest in how different aspects of system control would be distributed (e.g., competition agreements, length of concession contract, dispersion of control). The consequence of attributes that are not purely under the control of the system designer is that they do measure the perceived success of the airport express, but are of little help in decision making because the influence of the quality of the selected design does not drive these attributes very much. Many factors beyond the quality of service of the airport express for example drive average hotel room occupancy in downtown Chicago. Figure 4-4 classifies attributes according to these different hierarchy levels.

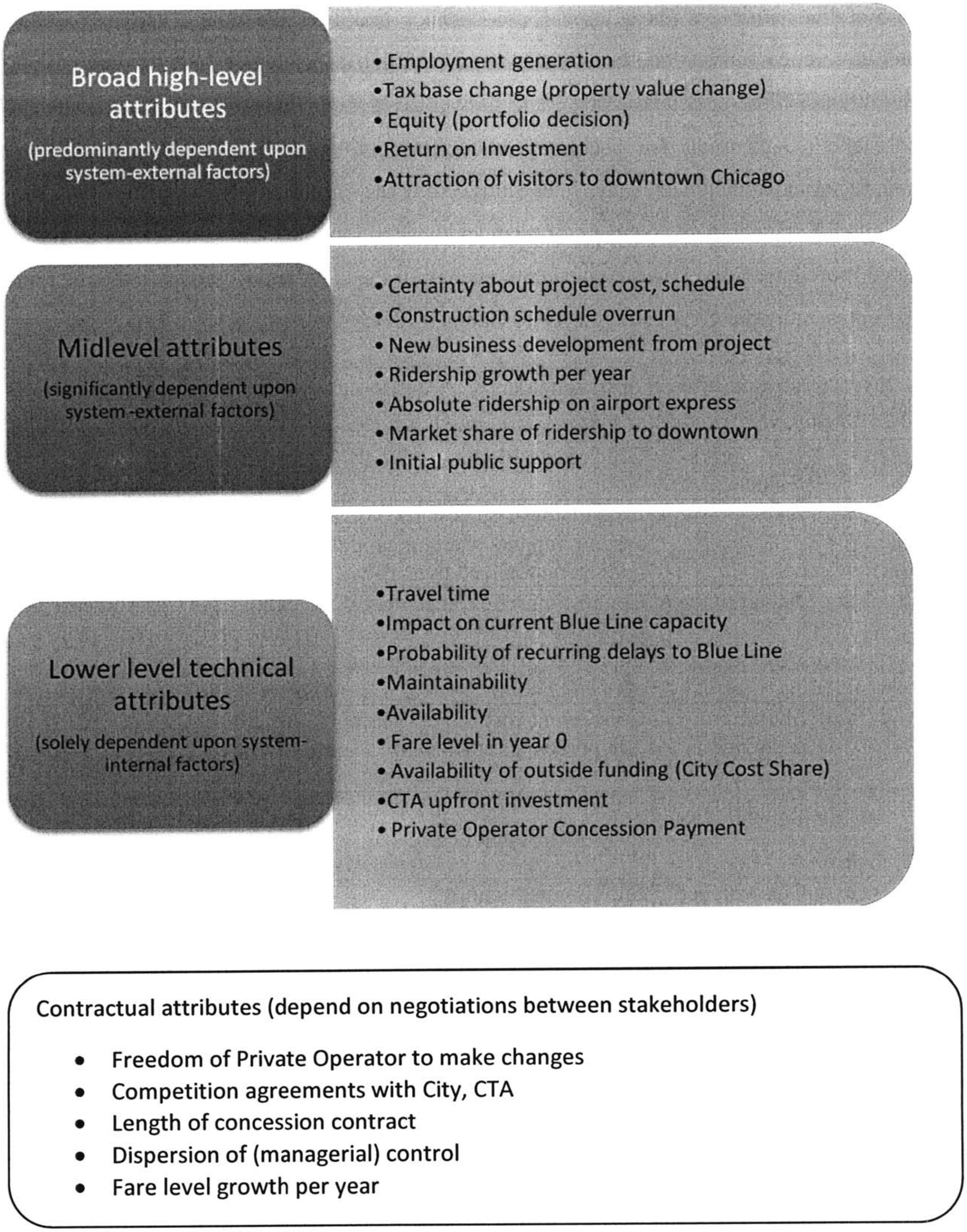

Figure 4-4: *Attribute hierarchy diagram*

Table 4-5 outlines attributes for additional, non-decision-making stakeholders, and are based on a Stated Preference Survey conducted by Wilbur Smith Associates at O'Hare International Airport (WilburSmith Associates 2004), and as well as domain expertise on what matters to different stakeholder groups. The lists are provided for completeness, but the attributes are not weighted or formally included in the later study. They are informally included insofar as the decision making stakeholders are aware of them and wish to include them in their own attributes. The Stated Preference Survey was conducted on behalf of the CTA and is known to the interview partners representing the CTA and the Private Operator.

4.4.2.4 MATE attributes for other stakeholders

Table 4-5: *Unranked attributes for non-decision making stakeholders (metrics in parentheses)*

Passengers-business	**Passengers-leisure**	**Chicago residents**	**Residents adjacent to tracks**
Reliability (schedule deviation)	Fare	Investment in other parts of CTA system (annual share in capital budget, annualized over 15 yrs)	Noise (decibel)
Travel time (min)	Travel time	Congestion relief on Kennedy Expressway (Level of service improvement during peak and off-peak hours)	Safety risks (risk increase in deaths and accidents per 1000 inhabitants from operation of new transit line)
Headway (min)	Shuttle from destinations downtown	Convenient way to get to airport (see passenger attributes)	
Baggage check-in down town (yes/no)	Reliability	Securing economic prosperity (jobs) in Chicago	
Convenience (Scale 1-5)	Convenience	Emission reductions	
Shuttle from downtown destinations (yes/no)	Span of service		
Span of service (hours)	Headway		
Fare ($)	Baggage check-in downtown		

The lists in Table 4-2- Table 4-4 illustrate that attributes elicited from the decision-making stakeholders in the interviews are different from the cost and benefits attributes elicited for the

CBA. Stakeholders in the interviews expressed a more agency-focused point of view pertaining to their respective organizations (whereby representation of the public interest is part of the agency mandate of the City of Chicago). This bias is expected and permitted when eliciting attributes for MATE, since attributes can be anything that a stakeholder is interested in (in the limits of the criteria for sets of attributes, as established in section 2.1.4.1), whether it can be monetized or not. Costs and benefits, on the other hand, have to satisfy a set of rules about what are and are not permissible attributes for a CBA, ensuring that only attributes are considered that are presumably of public interest (noise, emissions, price), and excluding those that are perceived as not being of public interest (concession payments, cost split, competition agreements). In addition, cost and benefit attributes need to be tangible and directly affecting the public to qualify as first-order effects. Any changes that are a consequence of first-order effects and affect the public are second-order effects, and are sometimes not recommended for quantification. Concession payments, cost split and competition agreements could therefore not be CBA attributes, since they do not directly affect the public. Direct effects that may result include, for example, possible changes to fare level, reliability, and frequency, and would need to be quantified in terms of those effects. All attributes for a CBA could be attributes in MATE, if expressed by a stakeholder, but not the other way around.

As it turns out, the attributes elicited through both methods are quite different. Attributes like congestion relief or emissions do not appear very prominently on the lists of the interviewed stakeholders. They do however appear on the list of non-decision making stakeholders. A difference needs to be noted between travelers and residents among the non-decision making stakeholders. Travelers are not formally involved in an official capacity in the planning process, but they do exert influence over the power to either withhold their money or give it to the operators of the airport express. Ultimately, as customers, travelers provide a significant income stream through fare payments to the system. If there is pressure to be profitable, the concern to meet customer needs provides an incentive to reflect their attributes in decisions. This feedback mechanism is weakened somewhat in situations in which there is either no alternative for a service (natural monopolies) or in which profitability is not achievable. In virtually all major US and European cities, public transportation systems require public subsidies on the order of 20%-70% of their total operating expenses, as was researched by the author and a fellow intern while at the CTA from publicly available balance sheets from the financial years 2005-2007. A systematic and comprehensive, but older, comparison of subsidy levels is available in (International Association of Public Transport (UITP) 2001). The findings on the existence and level of subsidies are however roughly the same.

If profitability is not achievable, the incentive to consider customer needs as a way to create more demand, and therefore potential profit, does not apply. Instead, the incentive is to reduce subsidies (which does not necessarily lead to more money in the pockets of transportation agencies, but rather result in more money in the pockets of the subsidizing government body). The question of how much pressure to be profitable should be imposed on transportation agencies is a matter of ongoing debate. On the one hand, it is desirable to have a market mechanism at work that provides a feedback mechanism between customer satisfaction and service. On the other hand, public transportation fulfills important societal functions, such as enabling mobility to underprivileged areas, which may never be profitable, but for which important reasons exist why they should be subsidized. A strict mandate to be profitable would force a transportation agency to cut less profitable services and to instead focus on other desirable areas, at the expense of desirable transportation services from a public welfare point of view.

In summary, some amount of feedback between travelers' satisfaction and the utility of the decision-making stakeholders is provided through the market, however to a lesser extent than would exist in a truly free market. Chicago residents and residents adjacent to tracks (recognizing that overlap between these groups exists) have a much less direct way of making their voices heard. They can protest in different ways, which is only likely if they are severely negatively impacted by a decision, because of the effort involved in protesting (collective action dilemma). Alternatively, Chicago residents and residents adjacent to tracks have influence through their voting behavior, which is an aggregation of satisfaction with a multitude of public policies and projects, and only occurs in election years. Therefore, the residents' attributes are only weakly reflected in the decision-making stakeholders' attributes apart from convenient accessibility of the airport and a desire for continued economic prosperity of the Chicago region.

4.5 Generate alternative system concepts (mode choice and corridor)

Four major concepts are evaluated in addition to the base case (minimal change to existing infrastructure): a direct rail connection on the existing blue line ("Direct Service"), a direct rail connection on its own dedicated right-of-way ("Express Service"), a bus rapid transit connection ("BRT"), and the transformation of the Blue Line into a dedicated right-of-way for the Airport Express ("Blue Line Switch option"), while local service would be substituted by a newly created bus system. Table 4-6 provides an overview of the concepts.

Table 4-6: *Overview of Airport Express concepts*

Nr.	Concepts	Abbreviation	Description
0	Base case	Base	Minimal improvement to status quo infrastructure
1	Direct service	Route 1	Train solution, shared tracks with local train
2	Express service	Route 2	Train solution, individual right-of-way
3	Bus Rapid Transit	BRS	Rapid buses on separate lane of Kennedy Expressway
4	Blue Line Switch	BLS	Rapid buses on separate lane on Kennedy Expressway replacing local train, Airport Express on freed-up tracks from base case

Since the first airport access improvement study in 1999, a dedicated rail express, either as direct or express service, were the only architecture concepts that were seriously considered in different studies (Trans Systems Corporation 1999; Parsons Brinckerhoff Consult Inc. 2006). The direct service is the cheapest option that was considered by the CTA (other than the base case), while the direct service was recommended as the result of a study that compared multiple possible rail corridors (Trans Systems Corporation 1999). The General Manager at the CTA who acted as proxy representative expressed that BRT was ruled out because of prestige concerns that might fail to attract the targeted premium audience (Interviews 2008). The analysis in this thesis compares two additional concepts to the ones suggested by previous: BRT and the Blue Line Switch Option.

Construction of a new downtown terminal in an area called block 37, near the Clark and Lake subway station in Chicago, had begun at the time of the internship in the summer of 2008. Since the CTA has committed to the construction and cost of the downtown terminal, the decision about the construction of such a terminal is not up for discussion in the concepts (Chicago Transit Authority 2005). The following section describes the architecture concepts in more detail.

4.5.1 *Base Case*

The Base Case denotes the option of using the existing infrastructure in an optimal way with minor improvements, but not major reconstruction. The FHA and FAA require the calculation of the performance of an optimally used status quo with minimal financial investment (base case) for CBAs prepared for official purposes in the US. For the purpose of this analysis, the Base Case is assumed to not involve any cost. Practitioners from the transportation consulting firm Parsons Brinckerhoff explained in a talk given to the class MIT ESD.225 "Urban Transportation Planning" in the Fall of 2008 that it is generally hard to prepare the base case for use in a CBA This is because the question of how to optimally use existing infrastructure at minimal upgrades involves quite a lot of research, especially since a sufficiently convincing case needs to be made to the reviewers of a CBA (if prepared for funding purposes) that the base case is indeed close to "optimal" use. Optimal use can of course never be verified, but the data gathering effort and thoughtfulness in preparing the base case must convince that this option received considerable attention. The base case analysis needs to be prepared very carefully, according to the speakers in MIT ESD.225, since reviewers will look at it especially closely and will more likely require rework than for any of the build-suggestions.

4.5.2 *Direct Service (Route 1)*

This corridor would utilize the existing Chicago Transit O'Hare Blue Line tracks between O'Hare and the new downtown terminal. Shared use of the existing Blue Line by direct trains and local trains to the airport presents several problems. The current running time from downtown (Clark/Lake) to O'Hare is 40-45 minutes. The targeted running time for improved airport service is on the order of at least 30 minutes to provide clear improvements compared to road travel. To achieve a running time of nearly 30 minutes on shared tracks, the direct train would have to pass 2-4 local trains since only one right-of-way exists in each direction. This operation would effectively restrict reliability of the airport express to that of the local train, since the airport express would need to wait in the bypasses for delayed "meet" trains (Figure 4-6).

The existing infrastructure is completely constrained by other structures, with very limited room to expand. From O'Hare, the Blue Line runs in the median of the Kennedy Expressway and completely fills its allotted right-of-way with its two tracks until near the Belmont station. Near

Belmont, the Blue Line enters a two-track subway. After the Logan Square stop it climbs onto an elevated structure and snakes its way towards the Loop through an alley adjacent to Milwaukee Avenue. Dwellings are just a few feet right and left from the alley. After the Damen station, the Blue Line drops into a second subway route which it continues until the Loop (Clark/Lake to La Salle stations). Figure 4-5 shows a list of Blue Line stops for reference.

Only three sites are available where passing tracks could be added without significant rebuilding costs. Two of these sites could be built for a minor cost (Option 1A, Figure 4-6). The disadvantage of these short passes is that precise timing from both local and airport trains is needed. Even minor schedule disruptions will cause a train to wait for its "meet" train, bearing the potential to severely interrupt the entire system. A variation on Route 1, labeled Route 1B in technical reports at the CTA, involves a major rebuild of the current track infrastructure to the airport. Parts of the Kennedy Expressway would be widened to accommodate large sequences of three tracks. A three-track subway line would be built to substitute the existing elevated tracks. Because of its prohibitive price, severe neighborhood disruptions and implementation time of over a decade, this option is not further considered.

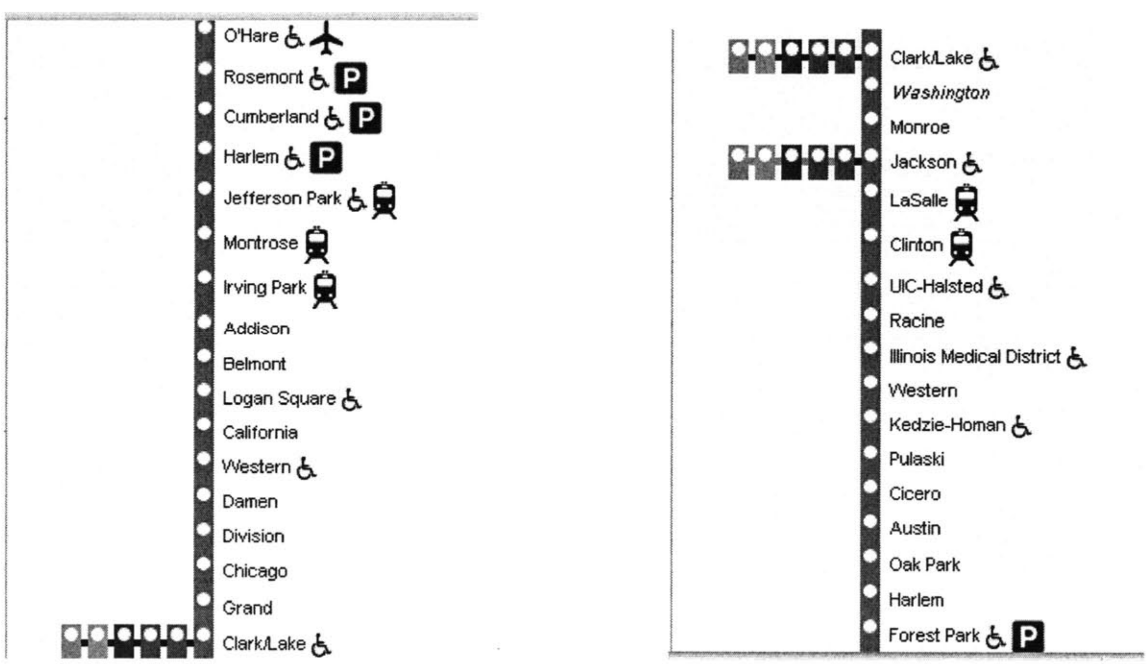

Figure 4-5: *Blue Line stations(Wikipedia 2008)*[11]

[11] Retrieved 12/06/2008, from http://en.wikipedia.org/wiki/Blue_Line_(Chicago_Transit_Authority)

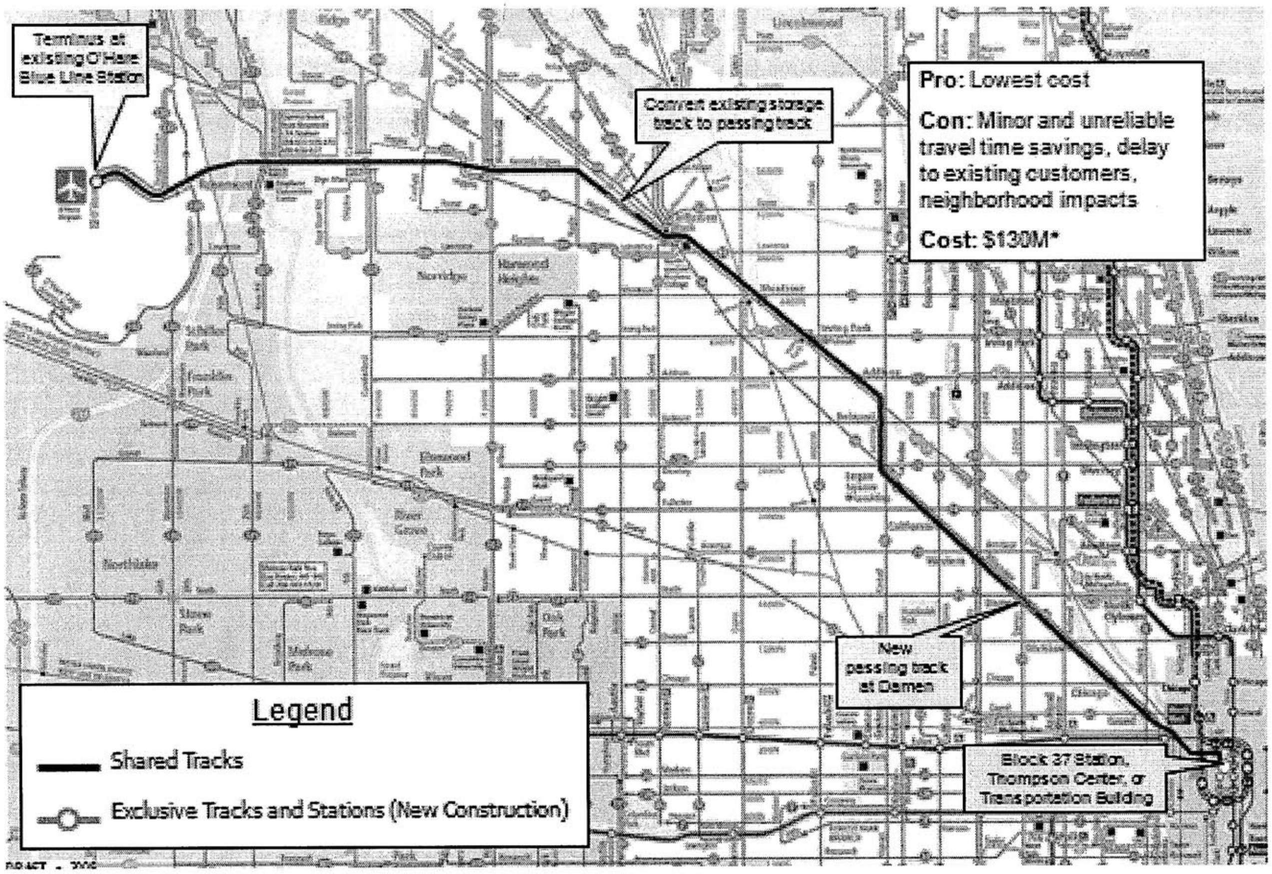

Figure 4-6: *Direct service (Source: CTA)*

4.5.3 Express Service (Route 2)

Express service denotes an airport train operating on its own dedicated right-of-way. A potential corridor for this option consists of unused tracks of the Chicago commuter rail system Metra.

Route 2 would use unused Metra tracks (Figure 4-7) containing three tracks on a four-track right-of-way. Rebuilding the fourth track would allow simultaneous Metra and Airport Express operations. A number of commuter rail stations would have to be rebuilt to allow reinstallation of the fourth track. During the last part of the route, the airport express would have to merge with existing traffic onto three tracks. This route could be operated reliably, and be built within two years. It makes possible fast running speeds because of the separate right-of-way for the airport express.

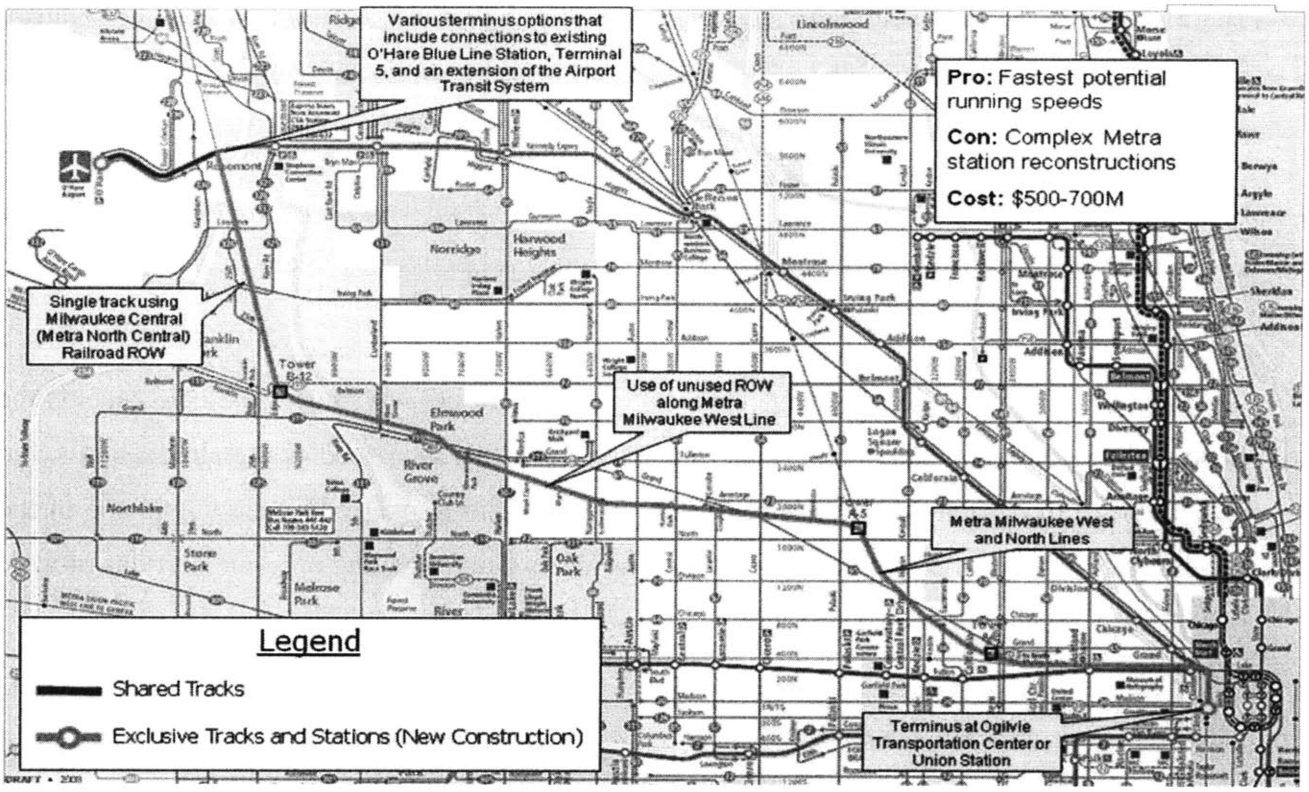

Figure 4-7: *Express service Route 2 (Source: CTA)*

4.5.4 Bus Rapid Transit

Bus rapid transit (BRT) is a broad term given to a variety of transportation systems that seek to enhance the quality of bus service to match that of rail rapid transit, while still enjoying the cost savings that bus service provides.

An important characteristic of BRT is a dedicated right-of-way, which improves speed and punctuality through relief from the regular traffic congestion that other vehicles face. In the densely populated inner metropolitan area of Chicago, the construction of a new right-of-way is not possible for most of the way to the airport without severely impacting neighborhoods (Figure 4-9). To ensure the required reliability for an airport express, BRT can realistically only be operated on a dedicated lane along the Kennedy Expressway. There are currently five lanes (Figure 4-8). An important question to answer is whether enough traffic can be relieved from the Expressway to offset the reduction in capacity from taking away one lane from general traffic. Capital costs of this option are minor, since only two new bus terminals would need to be built.

There are several options for how to get out of the downtown area and onto the Kennedy Expressway, on which most of the way to the airport would be traveled by rapid transit buses.

Option BRT 1 does not include a dedicated BRT lane along the Kennedy Expressway. The bus route proceeds from the downtown terminal via West Washington Street and the Kennedy Expressway to O'Hare, in a non-stop way. Travel time is effectively the same as for car travelers and subject to the same variance (Figure 4-2).

Option BRT 2 includes the same route as for option BRT 1, but with a dedicated bus lane on the Kennedy Expressway. This option would increase reliability and speed of the airport buses, but decrease overall capacity on the Kennedy Expressway. The Kennedy Expressway is one of the two busiest roads in Illinois with up to 327,000 vehicles daily traveling on some portions of it, so that a capacity decrease may cause serious (Wikipedia 2008)[12].

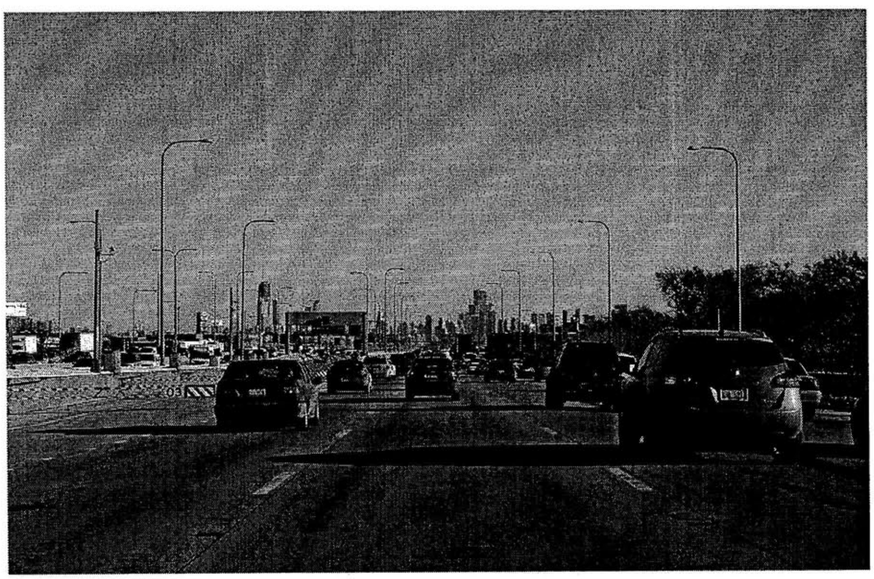

Figure 4-8: *Kennedy Expressway (Wikipedia 2008)*[13]

[12] Retrieved 12/06/2008, from http://en.wikipedia.org/wiki/Kennedy_Expressway
[13] Retrieved 12/06/2008, from http://en.wikipedia.org/wiki/Kennedy_Expressway

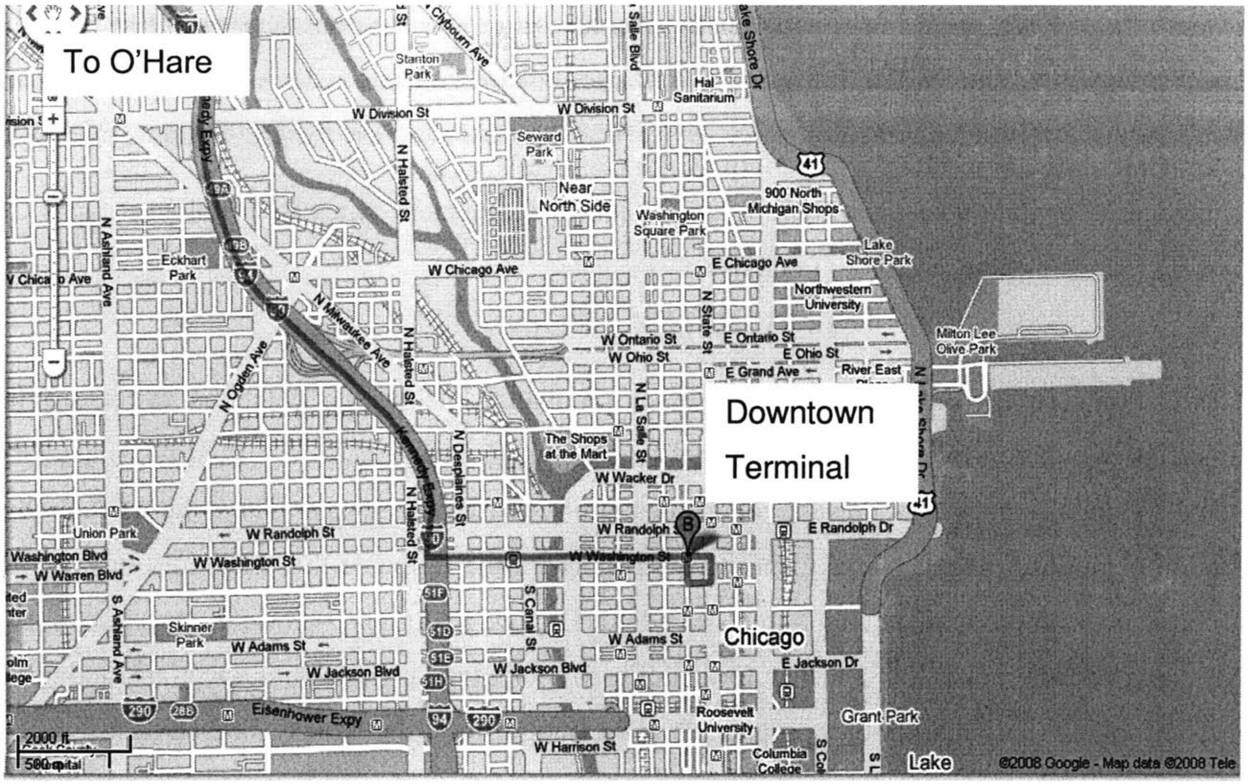

Figure 4-9*: Map of BRT portion downtown. Several ways exist for BRT to access the Kennedy Expressway, but no space for new rights-of-ways.(Google Maps 2009)*[14]

4.5.5 Blue Line Switch

For this new option the current Blue Line travelers would be diverted onto a new bus corridor to free up the CTA Blue Line. The CTA Blue Line tracks would then be used for a non-stop airport express with no or only minor changes to the structure. High-frequency, rapid transit buses on the Kennedy Expressway would replace local service along the current Blue Line. Since BRT buses fit fewer passengers than Rapid Transit cars, headways and consequently waiting time would be improved for users of the local service. An additional possibility includes the rerouting of some of the high-frequency buses to other local stops to provide improved door-to-door service for current Blue Line riders. The origin and demand pattern for such service changes would need to be examined separately to ensure that a net improvement is achieved. Two separate Blue Line Switch Options are examined: one that substitutes the Blue Line by a high-frequency BRT corridor along the Kennedy Expressway (Blue Line Switch 1), and one that uses

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[14] Retrieved 12/27/2009, from http://maps.google.com

a fleet mix of BRT, local buses and vans to provide better door-to-door service to former Blue Line riders (Blue Line Switch 2).

4.6 Calculate aggregate Cost-Benefit (CBA)

The generic formula for a Cost-Benefit calculation (for all benefit types B_i, for all cost types C_j, over T periods of time at discount rate d) is

$$\sum_{t=0}^{T}\left(\sum B_i - \sum C_j\right) / (1+d)^t = NPV$$

The resulting Net Present Value (NPV) resembles a financial net present value, but differs from a financial calculation in that costs and benefits are both monetary and quantified non-monetary items. While a financial net present value calculation is based on all cash flows, the CBA in this section excludes fare revenue as benefits or costs (with the rationale that they are transfers) in accordance with recommendations in (US Federal Highway Administration 2003). As such, the NPV as a result of a CBA is a metric for benefits to society at large, or public welfare, and not a metric for financial viability of a project. The first-order effects that are considered for this CBA are the following:

- capital cost (initial cost),
- operating cost (annual recurring cost),
- changes in emissions, and
- changes in travel time (delays or savings) to Blue Line riders, airport riders and drivers on the Kennedy Expressway.

A first analysis checking of compatibility with the minimal requirements is conducted in section 4.6.1. Before diving into detail, section 4.6.2 presents the Net Present Value results of the CBA. Monetary costs (capital and operating) are discussed in section 4.6.3, emission changes in 4.6.4 and travel time changes in 4.6.5. Although the minimally acceptable levels for an attribute were elicited in the MATE interviews, it is a reasonable assumption that an attribute level that would lead a stakeholder to abandon negotiations would be rejected at some point during the planning process. Using knowledge available from the MATE interviews here improves the CBA analysis since only design concepts that are basically acceptable to decision makers are analyzed. Since the modeling of costs and benefits is resource-intensive, typically more options are suggested initially than are evaluated later. Based on a top-down approach, some research is invested in a larger number of initial design suggestions, which are then reduced to the most promising ones for a complete CBA. It should be noted that the generation of solutions is a necessary prerequisite for CBA, but not a part of the method itself. The design concepts (explained in section 4.5) are based on CTA studies (Route 1, Route 2) and two additional suggestions developed by the author (BRT, BLS). The process of how these concepts were derived is not part of the discussion on the merits of CBA, since such processes are typically not well-documented, and are based on intuition and general experience of the involved planners. This step shares similarities with the concept-generation phase in MATE, in which ideas for general ways to solve the problem are brainstormed, and the derived concepts are varied creatively based on planners' ideas. In MATE however, this step of generating possible concepts to solve the design problem (and their systematic variation later on) is embedded in the process, whereas it is not for CBA.

Changes in travel time and changes in emissions values are labeled as either costs or benefits, depending on their change in relation to the status quo. Capital cost and operating cost are often pure cost types. The BLS option is an exception, since the cost from operating the current Blue Line will be saved and enter the equation as a benefit (the net operating costs for this option are negative too, however). Noise to residents and adverse neighborhood impacts from construction are qualitatively acknowledged, but not quantified at this point of the project. They are the kind of effects that would typically be analyzed in an Environmental Impact Statement at a later time in the planning process, along with requisites to mitigate those effects. Data about the extent of negative impacts is not available at the time of completion of this thesis (in fact, no official CBA has been conducted). Since the projects require construction costs in the area of several hundred millions of dollars, compensation payments would likely not change the order of magnitude of the project costs.

4.6.1 First analysis of promising options for compatibility with requirements

Table 4-7 provides an overview of basic cost and performance data for all discussed design options. The origins of the provided numbers are detailed in Table 4-8.

Table 4-7: *Basic cost and performance data of different airport express options*

	Vehicle cost	Construction Cost	# Vehicles required		Travel time	Schedule reliability
	(in 2008 $M)		Train cars	BRT	min	% on time
Route 1a	50.4	130	28	0	29	70
Route 1b	50.4	1330	28	0	25	95
Route 2	50.4	480	28	0	25	98
BRT 1	5.6	2.5	0	7	25-55	50
BRT 2	5.6	2.5	0	7	25	90
BLS	50.4	107	28	121	25	99

Table 4-8: *Sources of data points for Table 4-7*

Data point	Value	Source
Capital cost (2008 $M) for Route 1 and 2	1a- 130, 1b- 1330, 2- 480	Studies for Route 1 and 2 (WilburSmith Associates 2004)
Capital cost (2008 $M) for BRT and BLS	BRT $5.6M (new buses) + $2.5M (new station at O'Hare) BLS: $50.4 M (new train cars)+ ($102M (new buses)+$5M (new stations))	Internet research and class notes on cost of buses for BRT and BLS (Voith Group; 1.222 Management and Operations of Public Transportation Systems 2008)
Capacity of buses	Articulated bus (BRT): 110, Articulated bus (BLS, local service): 150, Standard local bus (BLS): 60, Vans: 15	Internet research and class notes on capacity of buses (1.222 Management and Operations of Public Transportation Systems 2008)
Travel time (min)	1a-29, 1b- 25, 2- 25	Studies for Route 1 and(Trans Systems Corporation 1999), Kennedy Expressway Statistics for BRT and BLS (GCM Travel Statistics 2008)[15]
Schedule reliability (% on time)	1a-70, 1b- 95, 2- 98	CTA studies for Route 1 and 2, author's reasoning for BRT and BLS (explained below)
# vehicles for Route 1 and 2	7 sets of 4 car-trains	(Parsons Brinckerhoff Consult Inc. 2006)
# vehicles for BRT and BLS	BRT- 7 buses, BLS- 28= 7 sets of 7 car-trains,	(Parsons Brinckerhoff Consult Inc. 2006)

[15] Retrieved 12/07/2008, from ttp://www.gcmtravelstats.com/Default.aspx?selLinks1=24.

The BLS option consists of 100% BRTs that offer the same level of service as the current Blue Line. Train cars are assumed to cost $1.8M each, local buses $300K each. Daily ridership on the Blue Line is 12,000 (Chicago Transit Authority 2008) during peak periods.

Since BRT would need to connect to the Blue Line in the Loop in downtown Chicago, the last part of each trip traverses the northwest downtown area. During rush hour, streets are usually highly congested and therefore decrease the otherwise high reliability of the BRT option. Therefore, BRT 2 was assigned a reliability of 90%. BRT 1 (no dedicated lane) was assumed to have a low reliability value of 50% because it travels on the congested Kennedy Expressway with its known high variance of travel time (Figure 4-2).

Based on the utility interview with the City of Chicago, a reliability level below 80% is not acceptable. This condition is not fulfilled for Route 1A and for BRT Option 1. These options are therefore likely to be rejected at an early stage and are not analyzed in more detail. Route 1B is not feasible from a cost point of view. According to the interviews, the City's maximum willingness to pay is 50% of the total project cost. This would be $665M for Route 1B. The CTA indicated its unwillingness to pay more than $100M. The private operator indicated a maximum concession payment of $60M for the concept direct service (Route 1), assuming profitability (which may or may not be the case). Direct service means that the airport express would share tracks with the CTA Blue Line except for a few bypasses. The maximum available funding adds to $760M and is a far cry from the projected $1.33B that would be needed for Option 1B. Option 1B is therefore rejected at this point. Table 4-9 summarizes the results of the considerations in section 4.6.1.

Table 4-9: *Options after preliminary feasibility analysis in CBA*

Design options	Rejected?	Reason
Route 1a	yes	Violates reliability requirement of 80% on time
Route 1b	yes	Cannot be financed based on willingness to pay information from stakeholder interviews
Route 2	no	-
BRT 1	yes	Violates reliability requirement of 80% on time
BRT 2	no	-
BLS	no	-

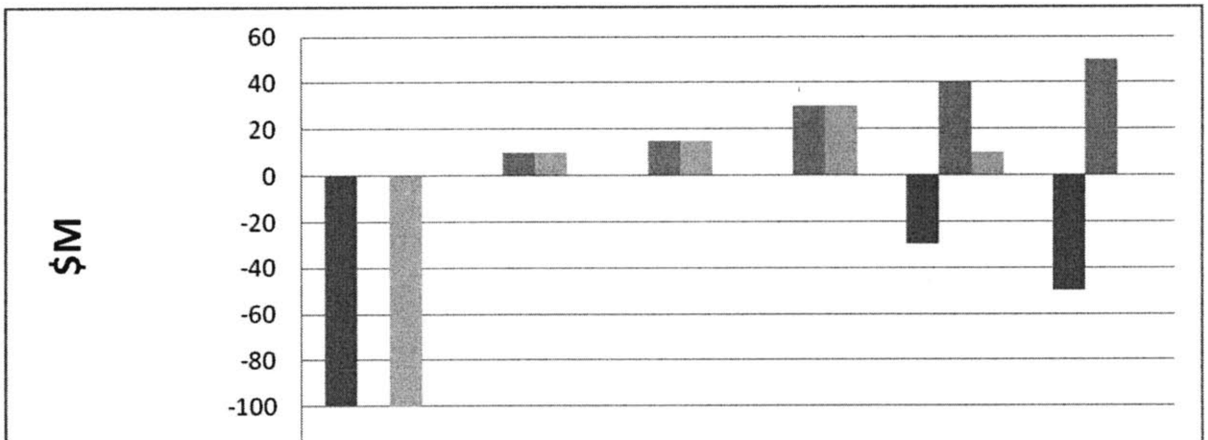
4.6.1.1 Net present value results from CBA

This section details the calculation process of the NPV values in Table 4-10. The generic formula for a Cost-Benefit calculation (for all benefit types B_i in period t, for all cost types C_j in period t, over T periods of time at discount rate d) is

$$\sum_{t=0}^{T}\left(\sum B_{it} - \sum C_{jt}\right) / (1+d)^{t} = NPV$$

Net cost or benefit "cash flows" for each design option were calculated in Excel for each of the assumed 50 years of useful life of the Airport Express. They are not real cash flows as understood in a financial project evaluation, since non-monetary effects are quantified and monetized in a CBA. The CBA "cash flows" for each year are added, discounted at discount rate d, and added.

Figure 4-10 illustrates the process of putting together the net cost or net benefit for each period of a system's life time.



t	1	2	3	4	5	6
■ Sum of costs in t	-100				-30	-50
■ Sum of benefits in t	0	10	15	30	40	50
■ Net result in t	-100	10	15	30	10	0

Figure 4-10: *CBA "cash flow" generation (example)*

The cost and benefit components used in this chapter are of the following four types, explained in more detail below:

- B_1 or C_1: Capital cost, consisting of the components of construction cost and vehicle acquisition;
- B_2 or C_2: Increases C_2 or reduction B_2 in operating cost;

- B_3 or C_3: Reductions (B_3) or increases (C_3) in emissions;
- B_4 or C_4: Savings (B_4) or increases (C_4) in travel time to different passenger groups.

It is assumed that in the BLS case all vehicles for the airport express need to be purchased new, since they will have different specifications than the current local train. The (old) discontinued local train is assumed to not be sold (but rather kept as back-up within the CTA system), therefore no monetary benefits from a sale accrue. "BLS-excluding former Blue Line" in the following refers to the cost of the system after subtracting savings from not operating the current Blue Line service anymore.

For the Net Present Value (NPV) calculations discount rates d of 7% and 10% were used. Seven per cent is a low discount rate as used by the US government for investment projects, whereas 10% is more representative of a discount rate used in industry (industry discount rates mostly refer to profit-seeking ventures, however). Most discount rates of interest will lie between 7% and 10%.

Ridership growth was assumed at 3.4% per year, which corresponds to the latest available growth forecast in enplanements at O'Hare by the FAA at the time of the preparation of the CBA study (Federal Aviation Administration 2006). Inflation was assumed at 3% per year and applied to both operating costs and fares. Train cars are assumed to be renewed every 20 years, buses every 15 years. The useful life of the airport express is assumed at 50 years (T=50). Because of the use of four-car trains, sufficient capacity for the growth scenarios is available in the options involving an airport train. Bus capacity is assumed to grow at the same rate as airport enplanements. This assumption is simplifying since buses are acquired in discrete increments, but it tries to take into account the fact that bus capacity can be adapted relatively flexibly because single vehicles can be purchased as warranted by demand.

The intent of the NPV calculation is to provide an order of magnitude estimate for an aggregate Cost-Benefit value to illustrate the use of the method. The author is aware that assumptions about inflation rate, ridership growth, enplanement growth, and electricity and fuel costs (the latter two are discussed in section 4.6.3) are extremely vulnerable to unforeseen developments. A comprehensive sensitivity analysis about these factors would be needed for an analysis on which technical decisions could be based. Similarly, the best choice of service parameters like fare and span of service and their impact on profit and ridership would need to be explored, for example through a sensitivity analysis.

Table 4-10 summarizes the outcome of the CBA analysis for the airport express options. All benefits and costs are understood as relative to the base case. Negative numbers represent savings to society and are therefore desirable, positive numbers represent added costs. BRT is beneficial across both considered discount rates (7% and 10%). Route 2 has a high initial cost, therefore this option appears better at the lower discount rate. The Blue Line Switch Option (BLS) does not provide any net benefit to society according to this analysis.

Table 4-10: *Quantified NPV of costs and benefits of feasible Airport Express options*

In $ 2008 M	**Base case**	**Route 2**	**BRT**	**Blue Line Switch (excl. former Blue Line)**
d=7%	0	-97	-70	718
d=10%	0	170	-37	447

The following section details the calculation of the benefit and cost components of the CBA equation:

$$\sum_{t=0}^{50} ((B_{1t} + B_{2t} + B_{3t} + B_{4t})-(C_{1t} + C_{2t} + C_{3t} + C_{4t}))/ (1+d)^t = \text{NPV}$$

The individual components are described below:

- B_1 or C_1: Capital cost, consisting of construction cost and vehicle acquisition, and (not applicable in the case study) income from sales of vehicles or infrastructure;
- B_2 or C_2: Increases C_2 (or reduction B_2 from discontinuing service) in operating cost, calculated for fuel cost, personnel (maintenance and operations) and vehicle replacement costs individually. Vehicle replacement costs here include the costs for annual fleet expansion of buses as warranted by demand. The reduction in operating cost occurs in the case of the Blue Line Switch option, in which the current Blue Line Service is discontinued;
- B_3 or C_3: Reductions (B_3) or increases (C_3) in emissions, calculated for the emission types CO (Carbon monoxide), NO_x (Nitrogen oxide), PM_{10} (Particulate Matter of of 10 micrometers or less), SO_x (Sulfur Oxide) and VOC (Volatile Organic Compounds) individually;

- B_4 or C_4: Savings (B_4) or increases (C_4) in travel time to Blue Line riders, airport riders and drivers on the Kennedy Expressway, calculated for each group individually.

The components (quantified first order effects) are treated in sections about (4.6.3) monetary costs (capital cost and operating cost), (4.6.4) changes in travel time and (4.6.5) changes in emissions.

4.6.2 Construction, vehicle and operating costs

This section lists the results of calculations for capital cost (construction + vehicle cost, Table 4-11) and operating cost.

Table 4-11: *Capital cost and basic performance data for feasible airport express options*

	Vehicle cost	**Construction Cost**	**# vehicles required**		**Travel time**	**Schedule reliability**
	(in $2008 M)		Train cars	BRT	min	% on time
Route 2	50.4	480	28	0	25	98
BRT	5.6	2.5	0	7	25	90
BLS (both)	147.4	10	28	121	25	99

Since the concepts BLS and "BLS-excluding former Blue Line" differ only in operating costs, they are listed together in Table 4-11. The BLS concept includes the cost of the new operations without subtracting the savings from not operating the Blue Line anymore for local service. "BLS-excluding former Blue Line" corrects for that mistake and is appropriate for comparison with other options. Operating cost (Table 4-12) is calculated in a bottom up approach by summing up costs for fuel, operation and maintenance personnel. The underlying assumptions for capital cost are listed in Table 4-8 and those for operating cost follow after. Route 1 is left out of the following calculations since it has been ruled out as an unacceptable option.

Table 4-12: *Operating cost data for feasible airport express options*

(in $2008)	Average Operating cost $/day		
	Fuel	Personnel-operations	Personnel- maintenance
Route 2	2,112	1,856	5,568
BRT	2,870	2,784	2,784
BLS -all	32,131	6,960	20,880
BLS- excl. former Blue Line	2,558	1,856	5,568

Data for fuel and electricity consumption in Table 4-12 was taken from the Millennium Database for the City of Chicago (International Association of Public Transport (UITP) 2001) and (Wikicars 2008)[16]. The roundtrip length for the airport express was taken from (Trans Systems Corporation 1999). The length of a local bus route in the BLS option was assumed at 25 miles per roundtrip, and van trips as 20 miles per roundtrip. The idea is that most trips in the BLS option will be shorter than the entire length from downtown Chicago to O'Hare, since the smaller vehicles can adapt better to customers' actual travel patterns, which do not always cover the entire length of the Blue Line. Diesel was assumed at $3 per gallon, electricity at $0.06 per kW-hr. Service span for the airport express is 16 hours for BRT and train service, as was assumed in the Parsons Brinckerhoff business plan (Parsons Brinckerhoff Consult Inc. 2006). The local service buses of the BLS options are assumed to operate 24 hours a day, like the current Blue Line. An hourly cost of $29 to the employer was assumed for bus or train drivers. Multipliers for maintenance and administrative overhead were used as follows: 4 for heavy rail, 2 for BRT, 1.25 for local bus and 1.1 for minivans. These numbers are assumptions based on lecture notes from MIT class (1.222 Management and Operations of Public Transportation Systems 2008), taught by Professor Nigel Wilson at MIT in the Spring of 2008. Headways (time between trains) for the airport trains are assumed at 15 minutes, and 10 minutes for BRT. This level of service is sufficient to accommodate 700 passengers per hour, which was assumed as peak demand for a daily demand of 5,000 people for transport to and from the airport.

Table 4-13 summarizes assumptions outlined in this section. The WAGs for ridership/traffic growth and inflation growth are intended to demonstrate that these effects exist and need to be considered. To refine the analysis it is important to vary scenarios for ridership and inflation

[16] Retrieved 12/05/2008, from http://wikicars.org/en/Fuel_efficiency

growth over the course of 50 years (useful life of the airport express). The years (2008-2009) in which this thesis was completed exemplified the rapid changes that are possible in demand for public transportation. Public transportation demand increased steeply in many American cities in late 2007 and 2008 following a surge in gas prices. By mid-2009, however, the average price for gas had decreased and car travel became more attractive again. The new era of increased demand for public transportation failed to materialize. Similarly, inflation prognoses are difficult in times of steep increases in public debt following the economic crisis. Epoch-Era analysis (section 2.1.3) is a tool for the systematic exploration of uncertain futures.

Table 4-13: *Summary of additional assumptions for operation costs*

Item	**Assumption**	**Source**
Bus replacement (BRT and local)	Every 15 years	Assumption based on industry best practice
Train replacement	Every 20 years	Assumption based on industry best practice
Initial ridership on Airport Express per day (year 0)	5,000	Estimate from (Parsons Brinckerhoff Consult Inc. 2006)
Initial ticket cost (year 0)	$16	Estimate from (Parsons Brinckerhoff Consult Inc. 2006)based on benchmarking of cost airport expresses worldwide relative to average cab fare
Annual ridership growth airport riders	3.4%	Same as FAA estimate for enplanement growth at O'Hare (Federal Aviation Administration 2006)
Annual ridership growth Blue Line riders	3%	WAG
Kennedy Expressway traffic	2%	WAG
Annual inflation rate	3%	WAG

4.6.3 Emission increases or reductions

Using an emissions model by the California Department of Transportation (California Department of Transportation)[17], the following values for emission impacts for the different options were calculated (Table 4-14). The increases or decreases in emission costs relative to the base case are included in the CBA. The monetary numbers of the adverse health effects from increased emissions are calibrated for rural California, and need to be treated with some caution. The linear increase in cost with increased emissions in this model is a simplification, since the

[17] Retrieved 12/11/2008, from http://www.dot.ca.gov/hq/tpp/offices/ote/benefit_cost/

"badness" of accumulation of pollutants in the atmosphere is non-linear and also depends on the presence of catalysts (for example, the sulfuric acid in acid rain (H_2SO_4) develops from SO_x in the presence of NO_2 as catalyst). The typical way in which a monetary value is assigned to emissions costs is to look for empirical data linking emission increases with increases in certain diseases or other environmental damage, and then to assess the monetary cost of treatment for such diseases, as well as the cost of remediation for environmental damage. An important factor for the calibration of costs from increased emission is its link to increases in related respiratory diseases, and the public health cost to treat those.

Even though standard economic theory (Viscusi, Vernon et al. 2000) maintains that a conceptually clear cut value for those costs exists, other authors (Heinzerling and Ackerman 2002) point out that there is in fact a large variation among monetary values assigned to increases in the same toxins. Differences may result from a variety of differing assumptions by the authors of such studies. An example of such an assumption is whether the marginal cost of the increase in respiratory diseases should be used as the reference point for cost, or if the cost of treatment for respiratory diseases should be divided equally between all cases.

A comparable emissions model to the CalDOT model for the Chicago area was not freely available. Differences in average temperature, base line pollution, cost of health care, population density, average population health, city vegetation and local geography in Chicago will result in changes to the values calibrated for Southern California, which should be kept in mind in a study for informed decision making. It seems that the colder climate and richer vegetation (due to higher precipitation, colder climate and conscious greening efforts in Chicago) would reduce air pollution in Chicago. On the other hand, population density in downtown Chicago is higher than in rural California, so that emissions produced by a larger number of people add up. Base line pollution is important for determining the marginal harm that will result from increases in pollution levels. Average population health and cost for providing (more) health care are non-technical factors that are important for monetizing the harm from increased emissions. The percentages of cars at different average speeds on the Kennedy Expressway were obtained from GMC traffic counts (GCM Travel Statistics 2008)[18] that are available online. The CalDOT model

[18] Retrieved 12/07/2008, from http://www.gcmtravelstats.com/Default.aspx?selLinks1=24

did not provide guidance on the size of the buses. The different kinds of buses in this study (articulated and standard size) are therefore treated the same for emissions values. It seems likely that the "bus" in the CalDOT model is a standard non-articulated bus that has a capacity of 50-60 passengers. The assumption to treat differently sized buses the same may put the BLS option at an advantage, since it transports large volumes of passengers in large, articulated buses, which may have a heavier polluting impact than is accounted for. The cars on the Kennedy Expressway are the main producer of CO-emissions. This is the reason why the values for CO are similar across different options. The Appendix contains equations and assumptions on constants of the CalDOT model.

Table 4-14: *Emission costs*[19]

	CO	NO_X	PM_{10}	SO_X	VOC
Route 2					
g/day	21,975,252	6,826,416	587,768	11,616	2,116,929
$/day	1,253	72,763	48,557	485	1,666
Sum $/day	**124,723**				
BRT					
g/day	21,974,047	5,730,617	463,785	12,490	2,085,937
$/day	1,253	61,083	38,314	521	1,642
Sum $/day	**102,812**				
BLS					
Sum g/day	22,479,632	3,842,909	237,562	15,281	2,089,108
$/day	1,281	40,962	19,625	638	1,644
Sum $/day	**64,150**				
Base case					
Sum	22,417,298	5,699,453	464,594	11,903	2,125,473
$/day	1,278	60,750	38,381	497	1,673
Sum $/day	**102,579**				

4.6.4 Changes in travel times and delays

The results of the calculations in this section are presented in Table 4-15 and Table 4-16. The results were calculated using traffic data about the Kennedy Expressway (GCM Travel Statistics 2008), CTA traffic counts (Chicago Transit Authority 2008) and ridership estimates from a business plan about the airport express (Parsons Brinckerhoff Consult Inc. 2006). The volume-speed relationship on the Kennedy Expressway was based on the volume-speed diagram in

[19] CO (Carbon monoxide), NO_x (Nitrogen oxide), PM_{10} (Particulate Matter of of 10 micrometers or less), SO_x (Sulfur Oxide) and VOC (Volatile Organic Compounds)

(Meyer and Miller 2001) which is included in Figure 4-11. Information about average wages to determine the monetary value of time savings was obtained from the US Department of Labor (US Department of Labor 2008). Travel time savings for different architecture concepts needed to be calculated separately. The calculations are detailed in section 4.6.5.1 (Route 2), 4.6.5.2 (BRT) and 4.6.5.3 (BLS). The three concepts for realizing express service to the airport (special train on Route 2, BRT on separate right-of-way, and special train on old Blue-Line tracks) are assumed to attract the same number of riders from current car travelers and Blue Line riders. Lacking preferential data and more detailed planning on all three options other than that they will have the same running time, they are assumed as equally attractive for calculation purposes.

Table 4-15: *Travel time savings in minutes to different stakeholder groups relative to status quo*

Travel time savings	**Airport travelers**	**Car travelers**	**Blue Line riders**
(min/day)			
Route 2	62,450	97,362	0
BRT	62,450	0	0
BL switch	62,450	0	261,000

Different sources recommend different approaches for the translation of time savings into money savings. Generally, the value of time savings is based on average hourly wages or a fraction thereof. Based on (US Department of Labor 2008), an average hourly wage of $30 for airport riders, and $20 for Blue Line riders is assumed. The difference seeks to take into account the higher share of high-income business travelers on the airport express compared to the Blue Line. Therefore, the monetary value of travel time savings is $31,225/day for airport travelers and $87,000 for Blue Line riders in the Blue Line switch option.

Table 4-16: *Monetary value of travel time savings based on average wages*

Travel time savings	**Airport travelers**	**Car drivers**	**Blue Line riders**
($/day)			
Route 2	15,613	16,227	0
BRT	15,613	0	0
BLS	15,613	0	43,500

Details on calculation of travel time savings for different architecture concepts

All feasible concepts (Route 2, BRT, BLS) operate at 25 minute running times and are hence easily comparable. Travel time savings are calculated in relation to the travel situation for different traveler groups prior to construction of an airport express (status quo). It may be a reasonable assumption that between 15%-30% of the 5,000 new airport express riders are diverted from public transportation on the current Blue Line. A 28% share is assumed for the calculation (1,400 travelers). The exact percentage share is unknown. Sensitivity analysis needs to be used to test the impact of varying this percentage share. The travel time for new airport express riders is 25 minutes. Based on average travel times to O'Hare (GCM Travel Statistics 2008), hourly car throughput can be calculated by referring to the volume-speed diagram in Figure 4-11 (Meyer and Miller 2001). The remaining 72% of the new 5,000 airport riders daily (3,600 travelers) are assumed to be diverted from car drivers on the Kennedy Expressway. Less people on the road means higher average speed and shorter travel times for the remaining car drivers on the Expressway. In order to calculate the congestion relief and number of people benefitting from it, the 3,600 diverted riders are assumed to mirror the general demand profile on the Kennedy Expressway over the course of a day (assuming the general traveler distribution applies to airport travelers in particular). A simple two-peak distribution of the 3,600 diverted travelers was based on Kennedy Expressway travel counts in Figure 4-2 and Appendix B and C. Once the number of diverted riders by traffic level (characterized by average travel speed) is known, the time saved by car riders diverted to transit and by car drivers remaining on the Kennedy Expressway can be calculated (Table 4-17). 1,380 car riders in total would be diverted during 8 night hours. They are excluded from the calculation since CTA plans preview a span of service of 16 hours for the Airport Express, excluding those night hours, and second because the streets are uncongested during those hours and travel time is low (17 min on average), so that the airport express seems less attractive from a travel time point of view. Jointly, 3,620 riders diverted from the Kennedy Expressway and 1,400 riders diverted from the former Blue Line add roughly to the projected 5,000 initial riders that (Parsons Brinckerhoff Consult Inc. 2006) assumed. From within a plausible range, the share of riders diverted from transportation was chosen such that it equaled the number of excluded would-be diverted drivers from the 8 night hours to facilitate calculations. A black font in the following tables indicates a description of the status quo, whereas lines with a gray font refer to the new situation with the Airport Express and calculations of travel time savings.

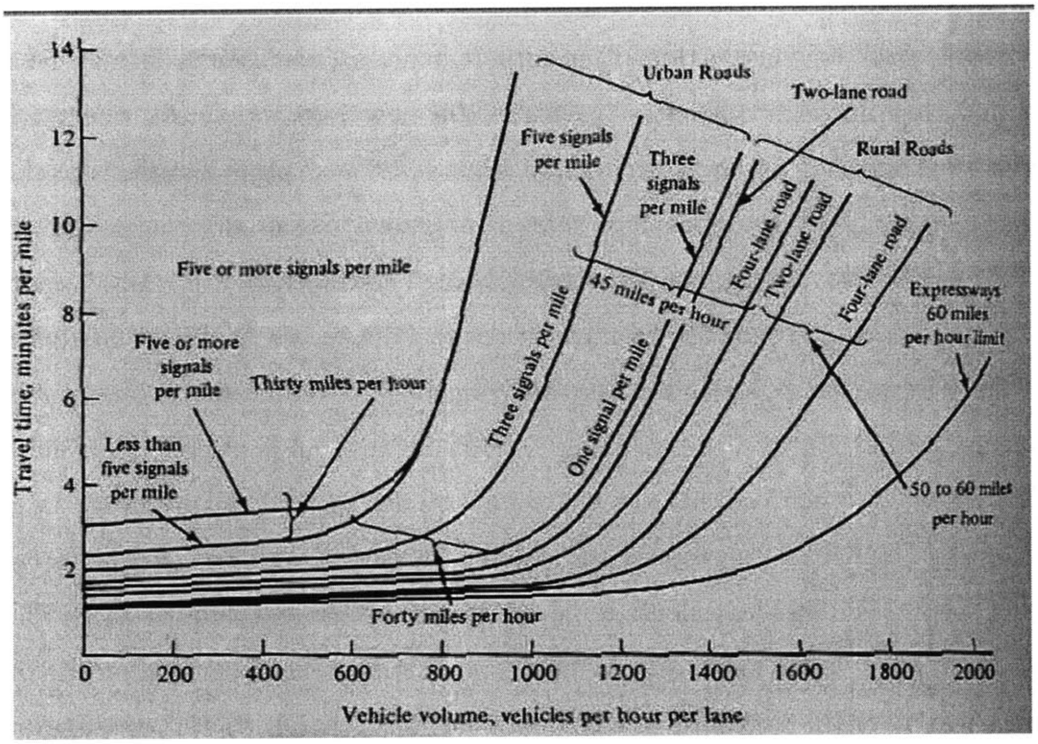


Figure 4-11: *Volume-Speed diagram (Meyer and Miller 2001)*

Travel time savings for Route 2

Table 4-17*: Travel time savings to airport-bound car drivers who switch to the airport express*

Traffic level on Kennedy Expressway	**1**	**2**	**3**	**4**	**5**	**6**	**7**
# cars/hr/lane	1,700	1,600	1,450	1,400	1,300	1,250	1,100
Speed (min/mile)	2.76	2.45	2.14	1.84	1.53	1.22	1.04
Speed (mph)	21.77	24.50	27.99	32.66	39.19	48.99	57.64
Travel time to airport (min)	45	40	35	30	25	20	17
Hrs/ day at that traffic level on Kennedy Expressway	3.00	2.00	2.00	2.50	3.50	3.00	8.00
% of traveler throughput during hrs at that traffic level	16	10	9	11	14	12	28
# of diverted cars to Airport Express/hr/lane ($\sum$ 362)	80	50	46	55	72	59	0
Travel time savings for diverted cars/lane/ traffic level	1.604	755	456	275	0	-295	
Travel time savings per lane/ day	2,795						

In the case of little traffic (traffic level 6) it would take passengers longer to take the Airport Express than to drive, so one advantage is lost. Mode choice to the airport is based on a number of factors, including reliability, certainty about travel time, price (airport parking, cab fees, express fare), convenience for travel with luggage, accessibility of the airport express downtown station and availability of a drop-off driver or airport parking. Because of the multitude of factors to consider, it is still assumed that the estimated 59 riders per hour per lane would be diverted and not all choose to drive based on the expected lower travel time alone. For lack of origin-and-destination data of airport travelers and availability of traffic counts for travel between the Loop and O'Hare, a fixed origin in downtown Chicago is assumed for all car drivers bound to O'Hare.

The 1,380 former Blue Line riders (airport travel time 50 min) who now take the Airport Express (25 min travel time) save a total of 34,500 minutes per day. Travel time savings for former car drivers is 27,950 minutes per day (2,795 min/day on 10 lanes). The estimate is conservative, since it counts one car as one person for travel time savings purposes. If the diverted car has more than one occupant, travel time savings apply to any additional riders as well. Jointly, the new Airport Express riders save (at least) 62,450 min per day. This value is independent of concept, since the assumptions are the same for diversion of travelers to the different but equally attractive architecture concepts for the airport express (Table 4-15).

Not only people who decide to ride the Airport Express save time, also the drivers who decide to stay on the Kennedy Expressway can move faster with less people on the road. Table 4-18 shows savings to car drivers from improved traffic conditions on the Kennedy Expressway. At an average wage of $20/hr per person, the travel time savings per day to drivers on the Kennedy Expressway are worth $32,454/day. Hrs/day at the reduced speed level remains the same as in the status quo, effectively excluding any induced demand. Induced demand is an important concern in all congestion relief scenarios. Induced demand is latent demand that manifests as transportation facilities free up. The underlying rationale is that travelers exist who previously chose not to travel by car, if other modes existed and were more attractive, or not to travel at all. As travel time is reduced for one transportation mode, the new situation brings about an increased level of demand. Fred Salvucci argued in his class on Urban Transportation Planning at MIT in the Fall of 2008, based on a variety of evidence for the phenomenon of induced demand, that "you cannot build your way out of congestion". While anecdotally widely recognized, empirical evidence and guidance for how to treat the phenomenon of induced demand is sparse (Cervero 2002).

Table 4-18: *Travel time savings to car drivers on Kennedy Expressway from improved traffic conditions*

New traffic level on Kennedy Expressway	1*	2*	3*	4*	5*	6*	7*
New # cars/hr/lane	1.642	1,564	1,417	1.360	1,248	1,208	1,000
New Speed (mph)	22	28	31	38	49	53.0	58
Hrs/ day at that traffic level on Kennedy Expressway	3.00	2.00	2.00	2.50	3.50	3.00	8.00
Travel time savings (min/day)	1.117	10,962	8,519	16,461	42,858	14,527	2,919
Sum	97,362	(min/day on Kennedy, all lanes)					

4.6.4.1 Travel time savings for Bus Rapid Transit (BRT)

The most important question for BRT is if the capacity reduction on the Kennedy Expressway can be offset by enough diversion of traffic to the Airport Express. BRT along the Kennedy Expressway would take away one of currently five lanes in each direction, thereby decreasing total capacity by 20%. Using the linear relationship between speed and travelers per hour from the volume-speed diagram (Figure 4-11), the data in the first 6 rows of Table 4-19 was obtained. Increasing traffic by 5% on the remaining 8 lanes at all times of the day leads to new traffic levels (indicated by a double star (**)) from which the resulting travel time increase compared to before can be calculated, assuming in this step that no traffic is diverted to transit (yet).

Table 4-19: *Travel time increases from reducing capacity by 20%*

Traffic level on Kennedy Expressway	1	2	3	4	5	6	7
# cars/hr/lane (10 lanes)	1,700	1,600	1,450	1,400	1,300	1,250	1,100
Speed (mph)	21.77	24.50	27.99	32.66	39.19	48.99	57.64
Hrs/ day at that traffic level on Kennedy Expressway	3.00	2.00	2.00	2.50	3.50	3.00	8.00
New traffic level on Kennedy Expressway	1**	2**	3**	4**	5**	6**	7**
New # cars/hr/lane (+ 5% cars, 8 lanes)	1,785	1,680	1,523	1,470	1,365	1.313	1,155
New speed (mph)	17.14	18.46	26.67	31.58	37.50	48.98	57.63
Travel time increase/ car/hr at new speed (mins)	16	20	3	2	3	0	0

Travel time increase/ per lane/hr (8 lanes)	28.929	32,943	4,548	3.019	3,695	17	5
Travel time increase per traffic level/lane/day	182,33 8	95.551	29.666	20,570	13.022	88	38
Travel time increase on 8 lanes per traffic level/day	1,458, 70	764,41	237,32	164,56	104,17	705	303
Sum travel time increase on 8 lanes /day	45.503						

Table 4-20: *Comparison of diverted and new traffic on one lane (daily)*

New traffic level on Kennedy Expressway	1**	2**	3**	4**	5**	6**	7**
Max # of pax diverted from given traffic level	134	126	114	110	102	98	86
72% of pax diverted from given traffic level	96	91	82	79	74	71	62
Increase in cars from reduced lane	85	80	73	70	65	63	55

Rows 2 and 3 of Table 4-20 show the potential relief by diversion from the Kennedy Expressway during certain traffic levels, each of which occur during a set number of hours per day (Table 4-19). If we assume that all new riders on the Airport Express were former car drivers, and we assume that their origin in terms of traffic level is proportional to the traffic flow during these hours, we derive the numbers in row 2. Row 3 repeats the exercise for a share of 72% former car drivers, as assumed earlier. Row 4 shows the number of additional travelers per lane per traffic level resulting from the capacity reduction on the Kennedy Expressway. Since the numbers for diverted car travelers at both 100% and even 72% are higher than the added drivers per lane, *the possibility exists* that all added traffic is offset. The number of diverted car travelers needs to be at least as high as the number of added cars, since every car brings with it at least a driver. Whether the capacity reduction will actually be offset depends on the actual percentage share of airport express riders among former car drivers, and especially the number of passengers per car that the former drivers were traveling in. If 72% of new airport express travelers were former drivers (as assumed in 4.6.5.1), average car occupancy would need to have been less than 1.13 to offset the impact of taking away one lane. This appears to be a low, but not unreasonable, estimate. Based on this calculation, it is likely that the worsened traffic from closing one lane is offset by the number of diverted drivers, or at least not very severe. BRT would then not strongly impact Kennedy Expressway drivers negatively. These calculations build on a market share of 5% for the airport express of total daily enplanements at O'Hare, or 5,000 airport express riders.

Even though the number was proposed for rail express, it is conservative enough to also be applied to BRT.

4.6.4.2 Travel time savings for BLS

Regarding the offset of capacity reduction on the Kennedy Expressway, the same considerations apply as for BRT. The capacity decrease on the Kennedy Expressway is likely to be offset or not be very severe. In addition, the proposed BRT operation for local service improves headways from the current 5 minutes, depending on the time of day, to less than 1 minute (40 seconds) during peak hours. Headways remain the same at 10 minutes during off-peak hours. This reduction in headway during peak hours would improve the waiting time of Blue Line travelers significantly. At a demand level of 12,000 travelers per peak hour on the Blue Line O'Hare branch per day (Chicago Transit Authority 2008) during 5 peak hours, would save 261,000 minutes daily in waiting time. Waiting time is calculated as half of the headway for high-frequency (walk-up) transit service, assuming a random distribution of passenger arrivals. This assumption is true for so-called walk-up service, where service is sufficiently frequent so that people do not plan their arrivals according to scheduled times. The quantification of the travel time savings in Table 4-21 is discussed in the beginning of section 4.6 and listed in Table 4-16.

Table 4-21*: Summary of travel time savings per option*

Travel time savings	**Airport travelers**	**Car travelers**	**Blue Line riders**
(min/day)			
Express	62,450	32,454	0
BRT	62,450	0	0
BL switch	62,450	0	261,000

4.7 Calculate aggregate Utility-Expense, plot tradespace (MATE)

In the previous steps attributes were elicited for decision making stakeholders, and system concepts were derived (general ways to solve a problem). In this section, the following steps are taken to generate tradespaces: (4.7.1), select attributes from interviews for the modeling effort, (4.7.2), isolate design variables, (4.7.3) sketch DVMs for each decision maker, (4.7.4) model underlying relationships between attributes and design variables, and (4.7.5) generate tradespaces.

4.7.1 Select attributes from interviews for model

The attributes elicited in the interviews (Interview partners 2008) give a sense of the interests of the different stakeholders. It is easy to see how attributes like "employment generation" or "return on investment" constitute a desirable measure for success for specific stakeholders. Those attributes depend, however, on a variety of influences that are only partially under the control of the designer of the Airport Express. Visitors to Chicago, especially those attracted by business purposes, certainly value a reliable method to get to the downtown area. Visitors do not, however, come to Chicago *because* of the Airport Express; it is the lack of convenient transportation that may lead people to take their business to other world cities that are competing with Chicago.

4.7.1.1 Attribute hierarchy

Four groups of attributes were distinguished in section 4.4.2 to roughly classify the attributes that were expressed in the stakeholder interviews (There may be ambiguity about one attribute between two groups when trying to apply this approach to other case studies; the four classes are however sufficient for a categorization for this particular case study.)

(1) *Broad high-level attributes* are predominantly dependent upon external factors in addition to factors that are influenced by the Airport Express. Except for major differences between architecture concepts, those attributes cannot adequately distinguish between any two different design concepts. (2) *Mid-level attributes* relate clearly to the Airport Express, but are significantly influenced by external factors in addition to technical ones. They are too broad to be "engineered for", in the understanding of clearly being determined by system-internal technical factors. (3) *Low-level attributes* depend solely and in a clear causal relationship on system-internal factors. (4) *Contractual attributes* are decoupled from decisions that affect the physical components or operations of the system. They refer to contractual agreements between the stakeholders. Figure 4-12 shows the attribute hierarchy tree, grouping the attributes according to these four categories, and now indicating which attribute each stakeholder is interested in. The City of Chicago expressed mostly high-level attributes, the Private Operator is interested in most contractual attributes, and the CTA contributed the most low-level attributes of the three stakeholders. All three stakeholders are relatively equally represented with attributes in the midlevel group.

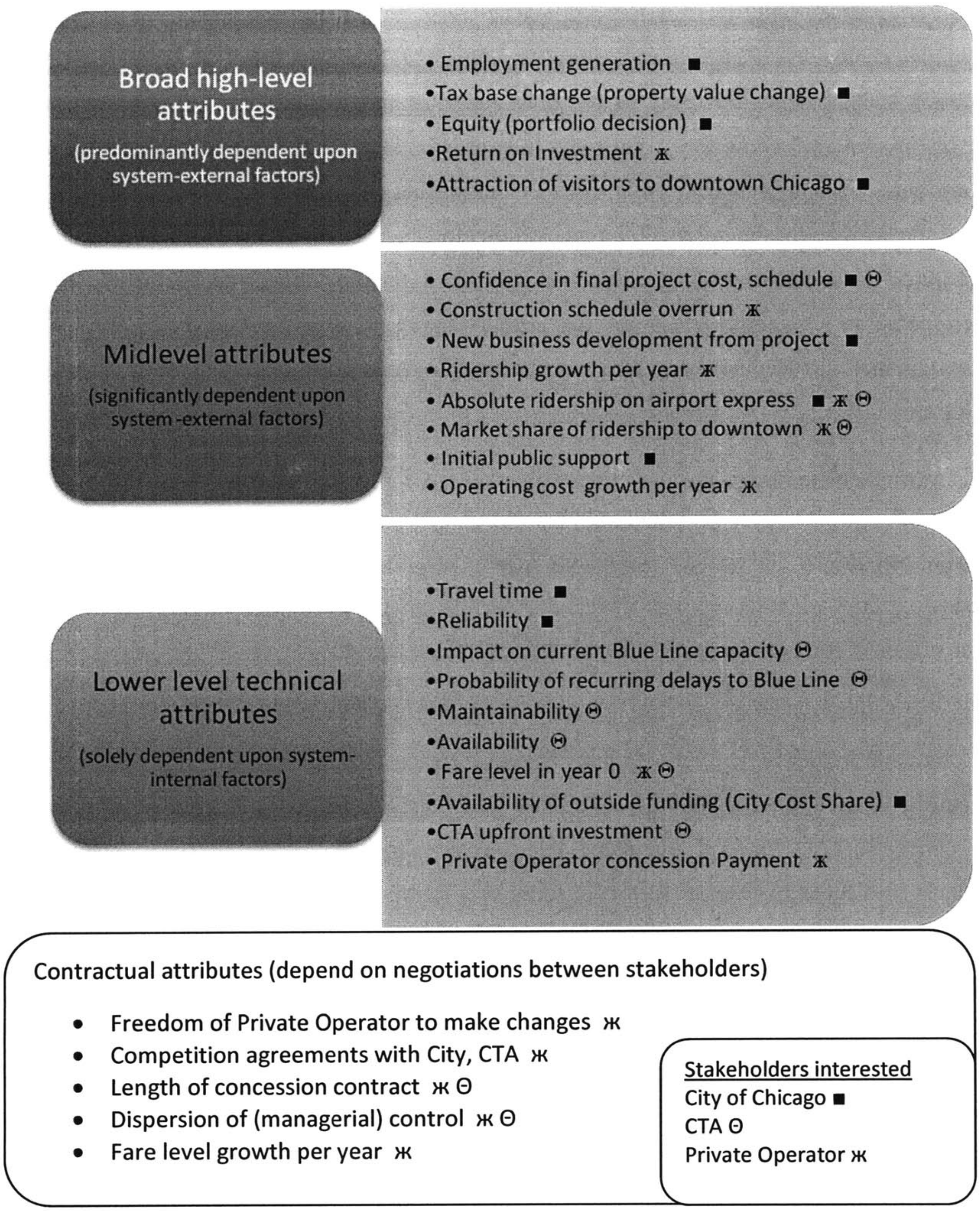


Figure 4-12: *Attribute hierarchy diagram*

Attributes that depend significantly or predominantly on system-external factors are not a "fair" measure of success for the Airport Express, even though they may be what a stakeholder is ultimately interested in. In order to derive useful metrics for decision making about different Airport Express architecture and design concepts, high-level and midlevel attributes will have to be decomposed into the underlying factors that influence them (Table 4-22). Of those factors, only attributes that are influenced to a significant degree by design variable choices are included in the decision making for this case study to distinguish between the goodness of different design concepts. This initiative appeared to be the best workable process to the author for including high-level and mid-level attributes into the decision making process in a way that actually helped differentiate between design concepts.

In section 4.4.2 attributes for non-decision making stakeholder groups (business and leisure travelers, residents adjacent to tracks, Chicago public) are listed. It is important to appreciate what attributes non-decision making stakeholders are interested in, even if they are not formally considered in the MATE analysis. Decision making stakeholders have, to varying extents, the mandate or other incentives to factor into their personal utility the utility of non-decision making stakeholder groups. The attribute "initial public support" of the City of Chicago reflects, for example, the concern for public acceptance, whereas basic customer satisfaction is a prerequisite for the Private Operator for generating fare revenue and possibly a profit. A market segmentation of airport express riders is a possible refinement to the analysis conducted. Since it is not necessary for the demonstrative purpose of this case study, airport express users are treated as a single group.

Whether the non-decision making stakeholders receive a "desirable" level of attention by the decision-making stakeholders as viewed by different points of advocacy (e.g., customers, tax payers, environmentalists) is a different question than the one of "what are efficient design solutions based on decision makers' subjective values?" Just as in reality, the influence of non-decision-making stakeholders is indirect and their concerns are (hopefully) reflected in the priorities of their representatives. The dependence of non-decision making stakeholders upon representation by decision making stakeholders is the reason why only the decision-making stakeholders are considered for the MATE analysis.

4.7.1.2 Decomposition of attributes

Only the top four attributes from the lists of attributes elicited were selected for the CTA and the Private Operator in order to simplify the case study for demonstration purposes. According to the weighting expressed in the interviews, this process captures 70% and 80% respectively of the weight the interviewees assigned among all attributes they enumerated. In the case of the City of Chicago, the weights were more equally distributed over the enumerated attributes, and the fourth and fifth attributes were tied. Therefore the top five attributes were considered in the case of the City of Chicago, accounting for 56% of the City's distributed weight.

The attributes in italics in Table 4-22 are those that the author identified as low-level attributes underlying higher-level attributes. Only the lower-level attributes in italics were selected for the modeling part of the MATE analysis, since it is necessary that the designer be able to influence them through the system design. It should be noted again that a number of the attributes, especially of the City and the Private Operator, are not specific to the airport express and would constitute reasonable goals for any public or private investment project, respectively. High-level attributes like estimated tax base change, employment generation, equity and return on investment are criteria that would likely be useful to differentiate at a high strategic level between two completely different projects, and hence be criteria for the portfolio decision (what projects to spend money on). An assumption for this case study is that the decision to build the Airport Express has been made, and that it is a priority. The question to be answered is therefore exclusively in what way the system should be realized. In reality however, the Airport Express competes year after year with other projects for space in the City budget. Even though the Airport Express has been recognized as a desirable project, the higher level portfolio decisions about desirable projects for a specific year are periodically reviewed. The review decides whether projects receive initial or continuous funding. This fact may be a reason why the top City attributes include criteria more suitable for the portfolio decision than for helping to guide conceptual design for this specific project.

Table 4-22: *Underlying factors for the City's attributes*

Weight	High-level Attributes	Depends on
0.12	Estimated tax base change	Land value ->Ridership-> Attractiveness -> *Quality of Service (QOS)*
0.12	Generation of employment	Attractiveness -> *QOS, City initial cost*

0.12	Availability of outside funding	*City cost share*
0.1	Attraction of visitors	Attractiveness -> *QOS*
0.1	Equity	*City's initial cost*
0.56	**Sum**	

Table 4-23: *Underlying factors for CTA attributes*

Weight	High-level Attributes	Depends on
0.2	Up front investment required from CTA	*CTA initial costs*
0.2	Capacity reduction on current Blue Line operations	*Shared tracks with Blue Line*
0.2	Probability of recurring delays to current Blue Line operations	*Shared tracks with Blue Line*
0.1	Maintainability	*Span of service*
0.7	Sum	

Table 4-24: *Underlying factors for Private Operator attributes*

Weight	High-level attributes	Depends on
0.4	Return on investment pre-tax	Ridership-> *QOS* (fares), *concession payment, operating costs*
0.15	Freedom of concessionaire to make operational changes	*Freedom to make changes*
0.15	Competition agreements	*Competition agreements*
0.1	Concession payment	*Concession payment*
0.8	**Sum**	

The following section discusses the decomposition of the higher-level attributes in Table 4-22 to Table 4-24: estimated tax base change, generation of employment, equity, and return on investment.

Estimated tax base change is a direct function of land value, which depends on several factors (accessibility, quality and maintenance of the building, properties of the surrounding neighborhood, etc), of which ultimately attractiveness of the Airport Express is the one that the system designer can influence. Land value in this context refers to the commercial area in downtown Chicago around the Airport Express terminal. The number of people (visitors, locals) who are attracted to the particular area around the downtown terminal as opposed to other parts of the City raises the land value around the terminal since they are potential customers for the surrounding businesses. Other factors that influence land value around the terminal include accessibility by other modes of transportation, the aesthetical and practical value of the commercial area for customers, and public safety. The attractiveness of the terminal area, located within the Loop, has a weak effect on the attractiveness of the Airport Express, whereas the influence the other way around (Airport Express on land value) is much stronger. Business around the downtown terminal is taking advantage of the flux of travelers, but seeing that the downtown terminal is already located in the dense Central Business District of Chicago, the businesses in the immediate surroundings of the terminal (hotels, restaurants, shopping) does not influence the attractiveness of the Airport Express strongly. In an (unlikely) extreme scenario, in which the area surrounding the terminal became, for example, a highly unsafe area with open shootings, the attractiveness of the Airport Express would suffer. If change in land value and its detrimental effect on Airport Express attractiveness is a concern, different scenarios and potential strategies for value-robustness can be explored by using Epoch-Era Analysis. For the present case, the concern is minor and therefore not considered further. The goal of achieving attractiveness for passengers is expressed by the attribute "Quality of Service" (QOS). QOS measures how well the (decision maker- perceived) needs of the stakeholder group "airport express users" are met. Different users will answer this question differently. A business traveler may prioritize reliability and travel time, whereas a leisure traveler or somebody who picks a traveler up from the airport will care more about a low price.

Generation of employment can refer to short-term employment generation from construction and to longer term employment generation from operation of the airport express and new business development as a result of a higher influx of tourists to the downtown area. Generation of employment is not easy to evaluate. Prof. José Gómez-Ibáñez argued in his class "Transportation Policy and Planning" at the Harvard Kennedy School of Government that jobs from construction activity can only be counted as project benefits if the workers in question were previously unemployed. General practice in CBA follows a simpler approach and tends to calculate "new" jobs from the amount of money that is spent on construction. Despite the clear relationship between construction and creating or securing jobs, caution needs to be taken not to equate construction expenses with generation of employment or other benefits. Theories of a multiplying effect of public investments assume that construction expenses end up in the pocket of someone (as opposed to paying for material), and that the money is spent again, ending up in the pocket of someone, being spent again from there, etc. The assumptions do not need to be true if money is saved or debts paid off. In addition, the "evaluation" translates costs directly into benefits regardless of the project in question, and does therefore not help to differentiate between different options.

The number of new employees for operation of the airport express is relatively constant. Parsons Brinckerhoff (2006) estimates the number of new jobs related directly to the airport express (operators, janitors, administration, etc) at 15. The required number of employees cannot be influenced by the designer other than through his ability to create an attractive (high quality) service that will expand and eventually require more personnel (the decision to needlessly employ people on the airport express or in construction for the sake of their employment is decoupled from the technical system design). Lastly, "new" jobs from a higher influx of tourists depend on tourists' decision to visit Chicago and ride the airport express. The controllable attribute again is attractiveness of the airport express, which translates to Quality of Service. The jobs of course are only new if the people who execute them were previously un- or under-employed, and did not just move their business a couple of blocks to where more customers are. All these considerations that are important for a CBA do not change the fact that the relevant attribute from a system design point of view is Quality of Service.

Equity denotes the amount of money that is spent on the Airport Express annualized over 15 years in relation to other projects. Based on the City budget and the acceptable range expressed by the City of Chicago, equity translates into City initial cost with an upper boundary. By thinking of equity in terms of a limited budget, the aspect of portfolio decision making is disregarded for the purpose of the analysis and the attribute becomes operational. In reality, of course, equity depends not only on the money spent on the Airport Express but also on the mix of projects that money is spent on. The portfolio decision is however beyond the scope of the system design of the Airport Express.

Return on investment depends in the profit equation. Profit (π) is a function of fare (p) times demand (q) minus (fixed and operating) cost (C) for a time interval.

$$\pi = p*q - C$$

The underlying attributes that determine profit are therefore concession payment (fixed cost), operating cost, and Quality of Service for the Private Operator (QOS_PO). QOS_PO seeks to reflect the Private Operator's utility from the combination of fare level and ridership. Ridership is assumed to be price-insensitive, which is a reasonable assumption for the premium segment of airport travelers (business travelers) that the Airport Express is expected to target. The number of riders, as far as the Private Operator is concerned, therefore depends exclusively on the service variables frequency, span of service, travel time, and amenities, which are discussed in section 4.7.2 on design variables. The City of Chicago however has a different Quality of Service attribute, in that a lower fare level contributes to utility because it will allow a larger number of residents to ride the airport express, who do not belong to the group of price-insensitive business travelers. Price elasticity of demand is defined as the responsiveness of the quantity demanded of a good or service to a change in its price. The concept is defined and expressed as an equation in standard microeconomics textbooks. Between the two goals of profit and ridership maximization, the assumption is that the Private Operator will not be able to impose a fare level higher than the monopolistic price (price elasticity of demand equals -1), and most likely will have to settle on a fare-level below the profit-maximizing monopolistic price. Therefore, an increase in fare level even at the loss of customers will strictly lead to higher profits for the Private Operator. The assumption is supported by the price-insensitivity of the customer segment in question. If price-elasticity for demand is known for fare level and ridership, the profit equation can be included as non-linear component into the model for ROI calculation. Empirical data on price-elasticity for demand for public transportation is not well researched, as discussed in MIT Class (1.222 Management and Operations of Public Transportation Systems 2008), and therefore often has to be treated in the form of a sensitivity analysis.

Table 4-25 summarizes the designer-controllable stakeholder attributes (attributes are those in italics from Table 4-22 through Table 4-24) and acceptable ranges for the further analysis in this section.

Table 4-25: *Attributes for the three decision makers*

Attributes	DM	Metric			Weight	Abbreviation
Expense			**Min acc e=1**	**Max acc e=0**		
City's initial cost	City	$M	640	200	0.16	CIC
City's cost share	City	%	50%	10%	0.12	CCS
CTA initial cost	CTA	$M	100	0	0.2	CTAC
Shared tracks with Blue Line (BL)	CTA	% BL capacity reduced	25%	0%	0.4	TRACKS
Operating costs	PO	$/day	25,000*	0	0.1	OC
Concession payment	PO	$M	500	0 (200)	0.2	CP
Utility			**u=0**	**u=1**		
QOS	City	Scale [1 to 5]	2	5	0.28	QOS
Span of service	CTA	Hrs/day	24	18	0.1	MT
QOS_PO	PO	Scale [1 to 5]	0	5	0.2	QOS_PO
Freedom to make changes	PO	Scale [1 to 5]	1	5	0.15	FC
Competition Agreements	PO	Scale [1 to 5]	3	5	0.15	AB

The acceptable ranges and measures are based on information from stakeholder interviews wherever applicable. The upper boundary for operating costs (*) was not discussed in stakeholder interviews (the attribute is a result of decomposition), and is varied in the tradespace exploration, with 25,000 being assumed as a default upper boundary. Attributes are categorized as either desirable or undesirable. Undesirable attributes are sought to be kept at a low level (either because they are harmful in any way or scarce). The distinction between utility and expense is not a rigorous one. It depends on the designer how to divide attributes into both groups to reflect multiple dimensions for each aggregate metric. Desirable attributes provide utility (u); undesirable attributes constitute expense (e). Below a utility level of u=0 or above an expense level of e=1 a stakeholder refuses his stake and abandons a project. Qualitative attributes such as QOS are measured on a scale of 0 to 5, where 0 denotes the lowest level of service and 5 the highest.

Concern for *reduced reliability of the Blue Line* is incorporated in the attribute "shared tracks with Blue Line". In the case of the BLS option, additional explanation beyond the non-existence of "shared tracks" is required to explain why capacity reduction and increased probability (the attributes that were reduced to "shared tracks with Blue Line" in Table 4-23) are not an issue. At the time of the interviews with the decision makers, shared tracks were the specified measure for capacity reduction or recurring delays for the Blue Line. The additional architecture concept of making the local Blue Line a rapid bus operation and using the freed-up tracks for the Airport Express was developed later by the author and included in the analysis. Tracks are not shared in the BLS alternative and are therefore not a feasible measure for any detrimental effects to the Blue Line, but concerns about capacity and reliability will still apply. Aware of those requirements, the BLS option was designed to have the same capacity as the current Blue Line, which happens to also translate to much shorter headways during the reliability-critical peak hours (> 1min peak) compared to the current Blue Line (5 min peak). Both the current Blue Line and BLS have 10 min headways during off-peak times, which tend to have less variation in boarding time and surrounding traffic and therefore less variation in running time (= higher reliability than peak hour runs). Together with the required new rolling stock for the BLS Blue Line (new rolling stock resulting in less break downs), it can reasonably be assumed that Blue Line reliability under BLS will remain at least the same as under the current service (The question is however still how to improve airport access, not how to redesign the Blue Line for local service. Expense is incurred if the Airport Express is detrimental to the current Blue Line service, but no value is gained if the Blue Line is improved as a result from any Airport Express option, because no attribute for Blue Line improvement exists (only for not making it worse)).

Improved reliability and accessibility of the airport express in comparison to existing airport access options were not considered in the attributes, despite their importance for QOS. The reason is that the factors that improve reliability appear to be largely design concept - independent (including achievable range) and would not differentiate between design options. Feasible architecture concepts are Route 2, BRT, and BLS. In the absence of competing traffic, reliability can be improved through improved maintenance, training, monitoring of staff (especially operators), and investment in new rolling stock to reduce breakdowns, but these measures are independent of the system design that is evaluated. Due to decoupling, strategies to improve reliability including the above actions are best evaluated in a separate analysis. Accessibility denotes the ease with which a user can access the downtown station. Since the downtown station is already under construction, decision makers are already "locked in" with performance in this attribute, therefore it does not vary between concepts and hence does not impact the analysis.

4.7.2 Isolate design variables

In addition to design variables that directly influence only one attribute (City cost share, freedom to make changes, competition agreements, CTA payment, span of service), design variables had to be isolated that drive attributes that depend on multiple factors. The question of perceived quality of service for different passenger segment was a key concern in classes about transportation planning that the author attended during her graduate studies at MIT. Frequency, reliability, fare, travel time, span of service, cleanliness and security came up regularly as the most important drivers of customer satisfaction in MIT classes and in discussions and talks at the CTA during the author's internship in 2008. Based on these experiences, the technical design variables fare level, frequency, travel time, span of service and amenities (e.g., laptop outlets, in-car information screens, comfortable seats) were chosen as the most important ones for the airport express. Cleanliness and security were excluded because they are non-technical intermediate attributes that influence Quality of Service, rather than technical design variables, and their discussion belongs in a more advanced stage of planning when detailed decisions can realistically be made. They are also largely architecture concept- independent. Security is provided by transit police in cars and in stations, whereas cleanliness depends on the janitors' number and quality of work. If either cleanliness or security are insufficient, additional investments in security and cleanliness (personnel, equipment) are one way to address the situation. Another one is to appeal to employees and passengers for cooperation. All measures drive the attribute operating cost. Since operating cost is only calculated on an order of magnitude level and decisions about how to address operational problems are too detailed to be usefully discussed at this point, cleanliness and security were excluded for conceptual design. The list of design variables in Table 4-26 summarizes design variables (DVs) and their enumerated ranges. The enumerated ranges for DVs 3 and 5 are based on assumptions by the author, since they were not discussed with proxy representatives at the time of the interview. All other technically feasible ranges are taken from (Interviews 2008). The proposed enumerated range for fare level is the intersection of the acceptable range [5, 20] for the City of Chicago and [10, 35] for the Private Operator, as expressed in the interviews.

Table 4-26: *Design variables*

DVs	Range	Measure	Abbreviation	Number
Concept	[1, 2, 3]	Route 2, BRT, BLS	Concept	1
Fare level	[10, 20]	$	Fare	2
Frequency	[5, 20]	headway in min	Freq	3
Travel time	[20, 30]	min	Time	4
Amenities	[1,2,3,4,5]	Qualitative Scale, 5 most amenities	Amenities	5
Span of service	[16, ...,24]	hr/day	Span	6
City cost share	[10, 50]	%	City Cost Share	7
Freedom to make changes	[1,2,3,4,5]	Qualitative Scale, 5 most freedom	Freedom	8
Competition agreements	[1,2,3,4,5]	Qualitative Scale, 5 most protection from competition	Competition	9
CTA payment	[0, 100]	$M	CTA	10

Fare level, frequency of service, travel time, amenities and span of service (hours of service per day) are the design variables that influence Quality of Service in the model. "Amenities" ranks the availability of features within the airport express bus or train (e.g., laptop outlets, in-car information screens, comfortable seats) on a scale from 1 to 5. The design factor "travel time" can be thought of as investments for speed enhancement in vehicles.

4.7.3 Sketch DVMs for each decision maker

A DVM is used iteratively to propose and select design variables that strongly drive attributes. In the sequence of steps for MATE, it is used before the final list of design variables is derived. The reason that it is presented in this thesis after the design variables is so that the reader will have an understanding of underlying design variables before seeing how they relate to attributes in a DVM. Basic thoughts about which design variables to include and which to exclude were provided in the previous section. The actual models described in section 4.7.4 were informed by the relationships as represented in Table 4-27, Table 4-28 and Table 4-29, but are not necessarily the same. It is therefore both an attribute and a design variable. A score of 9 indicates that the attribute is driven strongly by the respective design variable, a score of 3 indicates a medium influence, 1 a low influence, and a score of 0 indicates no influence.

Table 4-27: *DVM for the City of Chicago*

	Attributes		
Design Variables	**QOS_City**	**City's initial cost**	**City's cost share**
Arch. Concept	0	9	0
Fare level	9	0	0
Frequency	9	3	0
Travel time	9	3	0
Amenities	9	3	0
Span of service	9	0	0
City's cost share	0	0	9

Table 4-28: *DVM for the CTA*

	Attributes		
Design Variables	**CTA initial cost**	**Span of service**	**Shared tracks with Blue Line**
Up front investment requirement from CTA	9	0	0
Span of service	0	9	0
All other DVs	0	0	0

Table 4-29: *DVM for the Private Operator*

	Attributes				
Design variables	**Operating cost**	**Concession payment**	**QOS_PO**	**Freedom to make changes**	**Comp. Agreements**
Arch. Concept	9	9	0	0	0
Fare level	0	0	9	0	0
Frequency	9	0	9	0	0
Travel time	3	0	9	0	0
Amenities	0	0	9	0	0
Span of service	3	0	9	0	0
Freedom to make changes	0	3	0	9	0
Competition agreement	0	3	0	0	9

Quality of Service for the City (QOS_City) and Quality of Service for the Private Operator (QOS_PO) are two different attributes since they are modeled in different ways (perceived Quality of Service of the Airport Express by the City and by the Private Operator). The difference is the different valuation of fare level, which is explained in the next section. The attribute "Shared tracks with Blue Line" for the CTA differentiates between those architecture concepts that share tracks with the current Blue Line, and those that do not. Since all remaining feasible architecture concepts do not share infrastructure with the current Blue Line (only Route 1 did, which was eliminated), the attribute is the same for all considered architecture concepts (value for shared tracks=0%, e=0). Because of its inability to differentiate between design or architecture concepts the attribute "Shared tracks with Blue Line" for the CTA (indicated in gray) is excluded from the further analysis.

4.7.4 Model underlying relationships between attributes and design variables

MATE models can be of different forms, for example parametric models, formulas, bottom-up models, or look-up tables. An understanding of a basic mathematical representation of the causal relationship is a necessary prerequisite for the model development. In order to create parametric models, the modeling relationship also needs to be understood in a general way and not just from ex-post fitting and extrapolation of models to available data for specific examples. Intermediate variables are necessary intermediate steps when calculating attributes, but they do not provide value to stakeholders in their own right (Figure 4-13). For transparency and calculation speed, it is useful to call out one or several steps of intermediate variables. The equations in this section include constants. A list of constants and the source of their values is provided in Appendix 7.6.

4.7.4.1 Intermediate variable: Total construction cost

Total construction cost (TCC) is the only intermediate variable in this case study. It does not provide value to any stakeholder, but it is required to calculate cost shares and check combinations of cost contributions on feasibility with the cost of the remainder of the design vector (Table 4-30).

$$\underset{\text{Design variables}}{(DV_1, DV_2, \ldots DV_m)} \xrightarrow{\text{Technical model}} \underset{\text{Intermediate variables}}{(Y_1, Y_2, \ldots Y_k)} \xrightarrow{\text{Technical model}} \underset{\text{Attributes}}{(X_1, X_2, \ldots X_n)}$$

Figure 4-13: *Generic modeling steps for technical relationships in MATE*

Table 4-30: *Intermediate variable*

Intermediate Variables	**Range**	**Measure**	**Abbreviation**	**Number**
Total construction cost	unconstrained	$M	TCC	1

Equations for total construction cost:

```
Route 2
TCC=Route_2_construction_cost+Train_vehicle_cost+Amenities*More_amenities_cco
st_Route2+ (Low_travel_time-
time)*Reduced_travel_time_minute_ccost_Route2+(Low_frequency-
Frequency)*More_frequency_ccost_Route2

BRT
TCC=BRT_station_cost+BRT_vehicle_cost+Amenities*More_amenities_ccost_BRT+(
Low_travel_time-Time)*Reduced_travel_time_minute_ccost_BRT+(Low_frequency-
Frequency)*More_frequency_ccost_BRT

BLS
TCC=BLS_cost_of_new_buses+Train_vehicle_cost+Amenities*More_amenities_ccost_B
LS+(Low_travel_time-ime)*Reduced_travel_time_minute_ccost_BLS+(Low_frequency-
Frequency)*More_frequency_ccost_BLS
```

4.7.4.2 Directly controlled attributes

Five design variables translate directly into attributes. The different names for attributes and design variables (for essentially the same thing) is for clear differentiation only ("CTA" is the design variable CTA cost contribution, "CTAC" the attribute CTA cost contribution).

Attribute	Equation
City Cost share (CCS):	CCS=CityCostShare
City Initital Cost (CIC):	CIC= TCC*CCS
Freedom to make changes (FC):	FC=Freedom
Ability to make changes (AB):	AB=Competition
Maintenance time (MT):	MT=hours_per_day- Span
CTA Cost Contribution:	CTAC=CTA

The difference between the two attributes "City initial cost" and "City cost share" (CIC and CCS) is that the City has a value proposition not only for how much money it spends, but also for how much money it can attract per dollar spent through local matching of monies from other sources. The value propositions for the absolute monetary contribution and the percentage share of total cost of this contribution are therefore different.

"Competition agreements" and "Freedom to make changes" are attributes on a scale of 1 to 5. "Freedom to make changes" refers to the attribute that permits the Private Operator by contract to make operational changes (fare increases, schedule changes) without having to consult the CTA and City of Chicago. "Competition agreements" restrain the CTA and the City of Chicago in their ability to run competing services on the Kennedy Expressway, Blue Line, build competing streets or offer competing bus services in the future.

4.7.4.3 Quality of Service attributes

QOS for the City of Chicago is derived through an aggregation of the five factors fare level, frequency of service, travel time, amenities, and span of service. For the linear model, the permissible values are normalized over a scale from 1 to 5 each and added up, multiplying the fare value by two. The resulting number is divided by 6, to achieve an overall QOS value between 0 and 5. As a consequence, all factors contribute equally to passenger utility, except for reduction in fare price, of which reductions contribute the double amount of utility. More specifically, the following service improvements constitute each an equal amount of utility improvement:

- Reduction of price by $1.5 on a scale of $5-20
- Decrease of headway by 3 minutes on a scale of 5-20 minute headways
- Reduction in travel time by 2 minutes on a scale of 20-30 minute travel time
- Increase in amenities value by 1 on a scale of 1 to 5
- Extension of span of service by 96 minutes or 1.6 hour, on a scale of 16-24 hour service span

Quality of Service for the Private Operator is identical except for the treatment of the fare level: Higher fares increase the Quality of Service for the Private Operator (indicating high willingness to pay), whereas the City views lower fares as increasing Quality of Service so more people can ride.

<u>Equation</u>

```
QOS=((Scale_of_Five-
(Frequency_minus_Frequency_min/Normalizing_constant_for_scale_of_five)+
2*(Scale_of_Five-
Fare_minus_Fare_min)/Normalizing_constant_for_scale_of_five))
+(Scale_of_Five-
(Time_minus_time_min)/Normalizing_constant_time)+Amenities/Scale_of_Five+Span
_minus_workday/(Normalizing_constant_span))/Normalizing_constant_QOS
```

```
QOS_PO=((Scale_of_Five-
(Frequency_minus_Frequency_min/Normalizing_constant_for_scale_of_five)+2*
(Fare_minus_Fare_min/Normalizing_constant_for_scale_of_five))+(Scale_of_Five-
(Time_minus_time_min)/Normalizing_constant_time)+Amenities/Scale_of_Five+(Spa
n_minus_workday)/(Normalizing_constant_span))/Normalizing_constant_QOS
```

A note on pricing of transportation services with regard to utility functions

Pricing of natural monopolies, such as transportation services, is particularly difficult because three common ways to set prices do not work. In other industries, two common ways to determine the price of a product are cost-based pricing (full cost or at least marginal cost of production), or pricing to match competitors. In natural monopolies, no direct competitors are available to model prices after. In the case of the airport express the average cost of a cab ride to O'Hare from downtown Chicago (~$45) and of public transportation ($2) serve only as a very broad orientation. The suggested price range of $10-15 by the CTA is based on an internal study on fares for airport trains, which found that most systems around the world charge between 17% and 35% of the average cab fare for a one-way ride.

The second way to determine prices is that based on cost. Business administration teaches that to make a profit, goods need to be sold at at least the marginal cost of production. If they are sold for a higher price, the initial fixed cost expenses can slowly be repaid. After selling enough goods, the initial expenses are repaid and a profit is made. In the case of public transportation, initial investments are very high and recurring costs are comparably low, compared with other modes of transportation (International Association of Public Transport (UITP) 2001). Pricing at marginal cost of production will likely remain short of the expectation that at least some part of the initial expenses should be recuperated, let alone a profit be made. The analogous concept of production for transportation can be thought of as passenger miles, vehicle miles or passenger trips- each concept has its advantages and disadvantages since they are all no perfect measure for the service delivered. Lastly, full cost pricing is difficult because of the long time span into the future in which transportation benefits are gained and uncertainty about the number of riders. It is hard to determine the number of riders, and over what time period into the future, that should pay a transportation investment back. In addition, public transportation infrastructure is so expensive that in many cases initial investments will only be recuperated to a small share, if at all. A decision that the full cost of the investment should be born even by the first or second million of airport riders is not helpful, since the investment cost alone is on the order of several hundred million dollars.

The answer to the question if the Private Operator will make a profit depends on the required concession payment, profit expectations and discount rate used. The development of a model that would take into account the more complex relationships of price, market, uncertainty and different funding options is beyond the scope of this thesis.

It is clear from the modeling that if higher fares increase QOS_PO and come at no cost, that all Pareto-optimal designs for the Private Operator will maximize fares. In a decision making scenario with just one stakeholder, the Private Operator, this assumption would be too simple. In a multi-stakeholder decision space however, different views- e.g. advocacy for travelers' wellbeing and advocacy for profitability- can be represented by different stakeholders. The tradespaces then make explicit the tradeoffs for every individual stakeholder. There is, however, no algorithm in MATE that will determine a best solution in such a situation in which the same circumstance is evaluated differently by different stakeholders. This so-called evaluative complexity (Sussman 2002) has to be resolved in negotiations.

For the purpose of this model, the idea that higher fares contribute to the utility of the Private Operator and takes away from the utility of the City reflects a fundamental tension in the value propositions of these two stakeholders. The desires of the City is more aligned with the desires of actual passengers, whereas the desires of the Private Operator for QOS is more aligned to a business perspective on a good, which expects a services to be at good quality and be able to achieve a good price. It is important to bear in mind that QOS is not meant to reflect the expected ridership number. It is one factor that the designer can drive that influences actual ridership, but there are other factors at work that introduce uncertainty into the relationship from the point of view of the designer.

4.7.4.4 Cost attributes for the Private Operator

Operating Cost and Concession Payment are the two different kinds of cost that occur to the Private Operator. Even though both are paid in dollar amounts, they are two different "colors of money" and are therefore kept separate. The cost incurred by the City of Chicago is calculated from Total Construction Cost as explained above, whereas the initial cost for the CTA is directly controlled by a design variable. Operating Costs are contractually locked-in costs that the Private Operator owes the CTA annually. In return, the CTA will use its maintenance and operating staff to keep the airport trains running. The Private Operator would only oversee the marketing, sales, and general administration of the airport express. Based on contractual parameters, the Operating Costs that the Private Investor owes grow every year, in accordance with cost growth and hopefully ridership growth. The Operating Costs are therefore a recurring cost that is certain in the medium run (a few years), but will be renegotiated periodically. Uncertain future events, the history of the collaboration of the CTA and the Private Operator and the general success of the airport express will be important factors that influence the outcome of future negotiations. Even though the Operating Cost is dependent upon some contractual parameters, the idea is that the Private Operator reimburses the CTA for the outsourcing services they supply. There is a residual risk whose distribution between the two stakeholders has to be negotiated, but for the purpose of this study we assume that Operating Costs depend solely on the technical design, which will be the case in large part.

Additional hours of night service (increase in service span) in the operations cost model are twice as costly as service during the day to take into account overtime pay for late work or long shifts, and pay for full-day shifts since employees can only be deployed in 8 or 4 hour increments according to contracts with unions, and not for one hour individually when needed. A 16 hour working day fills exactly two eight hour shifts. If longer service into the night is desired, employees still need to be paid for half-day or full-day shifts plus any extra amounts for overtime or split shifts.

The Concession Payment is a one-time, up-front, fixed and certain payment. While there is confidence in the amount of the concession payment, on the downside it cannot be renegotiated depending on the success of the airport express. The concession payment is owed to the City of Chicago. Therefore, tradeoffs between the two kinds of expenses- operating costs and concession payment- include the difficulty that they will be owed to two different stakeholders. A larger concession payment can only be traded-off for smaller Operating Costs if some compensation were to be arranged between the City (that receives a larger concession) and the CTA (that receives lower recurring payments).

For the concession payment, the calculation is based on how valuable the airport express is to the Private Operator and how much he would be willing to pay for it (within the limits expressed in the interview). It is assumed that a Private Operator would value a train on its dedicated right-of-way more than a bus on a dedicated lane on the Kennedy Expressway. In the second case, the bus would still have to cut through congested inner city streets where no lane could be dedicated to airport service and there is a perception that customers may have a higher willingness to pay for a train than for a bus because it is "more exciting". This is the reason why the Private Operator would be willing to pay $100mn or $70mn extra, if the service was Route 2 or Blue Line Switch, respectively. Every additional point is worth $20mn in concession payment, while an extra amenity point is worth $5mn. Amenities are valued somewhat because they form part of initial vehicle expenses that the City will have to co-finance.

In addition, the model has a quadratic term consisting of the attributes Freedom to make changes and Competition agreements. Both attributes are complementary, since freedom in one dimension can easily be counterbalanced by the other stakeholders if little freedom exists in the second dimension. What the Private Operator really values is having free decision making power over the management of the airport express. This power can only be achieved if both factors play together. For Concept 1 and 3, the coefficient for the quadratic term is 10, and 20 for BRT. The reason behind this weighting is that BRT runs in much closer competition to cars and hotel shuttles on the Kennedy Expressway, and freedom to experiment with pricing, marketing, bundling, and shelter from competition will be more important than for the airport express trains, which are more unique.

Equations

```
Operating Cost
Route 2:

OC=Average_Fuel_cost_day_Route2+Average_personnel_operations_cost_day_Route2+
Average_personnel_maintenance_cost_day_Route2+(Span-
hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost
_day_Route2+Amenities*More_amenities_cost_Route2        +(Expected_travel_time-
Time)*Reduced_travel_time_minute_cost_Route2+(Low_frequency-
Frequency)*Reduced_headway_minute_cost_Route2

BRT:

OC=Average_Fuel_cost_day_BRT+Average_personnel_operations_cost_day_BRT+Averag
e_personnel_maintenance_cost_day_BRT+(Span-
hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost
_day_BRT/hours_per_workday+Amenities*More_amenities_cost_BRT
+(Expected_travel_time-
Time)*Reduced_travel_time_minute_cost_BRT+(Low_frequency-
Frequency)*Reduced_headway_minute_cost_BRT

BLS:

OC=Average_Fuel_cost_day_BLS+Average_personnel_operations_cost_day_BLS+Averag
e_personnel_maintenance_cost_day_BLS+(Span-
hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost
_day_BLS+Amenities*More_amenities_cost_BLS          +(Expected_travel_time-
Time)*Reduced_travel_time_minute_cost_BLS+(Low_frequency-
Frequency)*Reduced_headway_minute_cost_BLS


Concession payment (how much money Private Operator is willing to pay to
operate a given system)

Route                                                                      2:
CP=Concession_fix_Route2+Competition*Less_competition_willingness_to_pay_Rout
e2+Freedom*More_freedom_willingness_to_pay_Route2
+More_freedom_and_less_competition_together_willing_to_pay_Rte2*Competition*F
reedom+Amenities*More_amenities_willingness_to_pay_Route2
```

```
BRT:
CP=Concession_fix_BRT+Competition*Less_competition_willingness_to_pay_BRT+Fre
edom*More_freedom_willingness_to_pay_BRT
+More_freedom_and_less_competition_together_willing_to_pay_BRT*Competition*Fr
eedom+Amenities*More_amenities_willingness_to_pay_BRT;

BLS:
CP=Concession_fix_BLS+Competition*Less_competition_willingness_to_pay_BLS+Fre
edom*More_freedom_willingness_to_pay_BLS
+More_freedom_and_less_competition_together_willing_to_pay_BLS*Competition*Fr
eedom+Amenities*More_amenities_willingness_to_pay_BLS
```

4.7.5 Formulate utility and expense functions

The equation for the generic linear weighted sum utility function is:[20] The fraction $\frac{xi-\min(xi)}{(\max(xi)-\min(xi))^{\wedge}\gamma}$ represents the i different single-attribute utility functions.

$$U_x=\sum_{xi} w_i*\frac{xi-\min(xi)}{(\max(xi)-\min(xi))^{\wedge}\gamma}$$

The equation for the generic weighted sum expense function is:[21]

$$E_x=\sum_{xi} w_i*\frac{xi-\min(xi)}{(\max(xi)-\min(xi))^{\wedge}\delta}$$

A diminishing return function (γ= 1/2, δ=1/2) underlies utility and expense functions in the tradespaces unless otherwise specified.

The expense function for the City of Chicago is a linearly weighted function consisting of the two inputs City initial Cost (CIC) and City's Cost Share (CCS). The factor 0.57 (= 0.12/0.22) is the weight for CIC, and the factor 0.43 (=0.10/0.22) for CCS. The different coefficients

[20] x_i denotes Attribute i, w_i denotes the normalized linear weighting factor for attribute I, γ characterizes shape of utility function

[21] x_i denotes Attribute I, w_i denotes the normalized linear weighting factor for attribute i, δ characterizes shape of expense function

correspond to the higher weight of 0.12 for construction costs and the lower weight of 0.10 for the cost share that were assigned in the stakeholder interview (Table 4-2).

QOS is the only utility providing attribute for the City of Chicago and has a k_i – value of 1.

The CTA has two attributes that can be influenced by the remaining designs: Maintainability (benefit) and CTA contribution to initial expenses (cost). These two attributes map directly, linearly, and continually over their acceptable ranges to the utility and expense functions for the CTA, whereby however a utility of 1 is achieved for maintainability time of 6 hours or more.

Utility for the Private Operator is calculated from three attributes: QOS_PO (QOS for Private Operator, which is different from QOS for the City of Chicago), Freedom to make changes and Competition agreements. QOS_PO is weighted by a factor of 0.4 and Freedom to make changes and Competition agreements by a factor of 0.3.

Expense for the Private Operator is calculated from the attributes "Operating Cost" (weighted at 0.43) and "concession payment" (weighted at 0.57).

4.7.6 Generate tradespaces

Tradespaces were generated using a random sampling algorithm across the design variable enumeration ranges listed in Table 4-26 for evaluating alternative design options. Depending on the increments between enumeration levels of design variables, the size of the design space is on the order of a few billions of designs. The size of the design space is 3.6B for 1min-increments for all time attributes, 10%-increments for the City cost share and $10M-increments for the CTA cost contribution. The tradespaces were plotted in MATLAB® for a design space size of n=20,000. The actual yield of financially feasible designs however is lower. Designs in which TCC does not correspond to the sum of CIC, CP and CTA are rejected as financially unfeasible.

Utility is aggregated through a utility function on the y-axis, whereas aggregated expense is displayed on the x-axis. The red line indicates the Pareto Front, consisting of the designs that provide the highest utility for a given expense level. The design vectors for the Pareto optimal designs for all three stakeholders are provided in the next section. All tradespaces in this section are colored by concept choice (DV1).

4.7.6.1 Pareto Optimal designs

The Pareto optimal designs are listed in order of ascending utility. They are not numbered since they are a random drawing of designs(Table 4-32, Table 4-33, Table 4-34).

Table 4-31: *"Cheat Sheet" Design Variables*

DVs	Range	Measure	Abbreviation	Number
Concept	[1, 2, 3]	Route 2, BRT, BLS	Concept	1
Fare level	[10, 20]	$	Fare	2
Frequency	[5, 20]	headway in min	Freq	3
Travel time	[20, 30]	min	Time	4
Amenities	[1,2,3,4,5]	Qualitative Scale, 5 most amenities	Amenities	5
Span of service	[16, ...,24]	hr/day	Span	6
City cost share	[10, 50]	%	City Cost Share	7
Freedom to make changes	[1,2,3,4,5]	Qualitative Scale, 5 most freedom	Freedom	8
Competition agreements	[1,2,3,4,5]	Qualitative Scale, 5 most protection from competition	Competition	9
CTA payment	[0, 100]	$M	CTA	10

Table 4-32: *Pareto optimal design vectors for the City of Chicago*

	DV	1	2	3	4	5	6	7	8	9	10
Utility	Expense	Conce	Fare	Frequer	Time	Amenit	Span	CCS	Comp Ag	Freedc	CTA con
0.549561	-1	2	16	18	21	1	23	0.1	3	5	19
0.583211	0.248014	2	20	19	22	1	22	0.3	2	4	36
0.588314	0.262382	2	19	8	20	1	24	0.2	1	5	70
0.60488	0.275923	2	20	17	27	1	22	0.3	2	4	73
0.609048	0.279205	2	20	19	27	2	19	0.2	2	5	85
0.61047	0.309767	2	18	16	21	1	17	0.3	1	4	96
0.617931	0.416963	2	18	18	21	1	17	0.4	1	4	8
0.631393	0.457444	2	18	8	23	1	23	0.5	2	5	25
0.633078	0.473666	2	19	8	29	2	23	0.4	3	5	84
0.637991	0.47409	2	18	17	25	1	23	0.4	1	5	32
0.645991	0.478715	2	19	17	29	1	19	0.4	1	3	36
0.64744	0.487329	2	15	17	20	1	21	0.3	1	4	44
0.649076	0.491735	2	20	19	23	3	23	0.3	1	4	43
0.650571	0.496073	2	16	19	24	1	19	0.1	1	5	83
0.655127	0.498022	2	18	5	29	1	23	0.3	1	5	42
0.660905	0.504175	2	19	7	23	4	23	0.3	5	5	25
0.662391	0.510572	2	18	13	27	1	17	0.2	1	4	15
0.667416	0.524004	2	20	8	24	2	21	0.2	3	5	46
0.672708	0.528851	2	19	17	26	3	23	0.2	3	5	8
0.677349	0.560683	2	17	19	29	1	20	0.3	1	3	7
0.682202	0.576727	2	20	7	21	4	20	0.2	3	5	5
0.686603	0.598812	2	20	18	21	2	18	0.3	1	5	8
0.699514	0.599481	2	20	5	23	4	21	0.2	3	5	55
0.705347	0.606812	2	11	19	29	1	23	0.3	1	5	36
0.709975	0.616157	2	18	17	26	1	23	0.4	2	5	75
0.725637	0.618399	2	17	20	21	2	23	0.3	3	5	82
0.727483	0.654275	2	17	18	21	1	18	0.5	1	3	51
0.746125	0.65833	2	18	10	26	1	20	0.2	1	4	16
0.755449	0.6744	2	16	19	25	1	20	0.1	1	4	46
0.761466	0.67582	2	18	7	27	2	23	0.2	3	5	71
0.770161	0.676527	2	20	17	28	2	19	0.4	1	3	93
0.771621	0.694731	2	19	18	21	1	22	0.3	2	4	46
0.789607	0.712721	2	20	14	21	3	24	0.4	3	5	46
0.789747	0.724307	2	18	13	25	2	23	0.2	2	5	13
0.794632	0.730793	2	18	9	28	1	24	0.3	2	4	46
0.796025	0.744317	2	19	9	23	1	18	0.4	3	5	53
0.805534	0.76077	2	18	7	23	2	24	0.1	2	5	10
0.820445	0.762197	2	20	18	22	1	21	0.4	1	3	50
0.830722	0.782599	2	20	9	30	1	18	0.4	1	4	51
0.843897	0.79176	2	19	17	23	4	23	0.4	1	5	66
0.85954	0.801947	2	14	19	28	1	22	0.3	1	4	15

0.901316	0.804479	2	20	5	21	3	21	0.3	2	5	72
0.901683	0.813905	2	17	17	29	1	21	0.3	1	4	57
0.90414	0.815667	2	16	19	29	2	23	0.4	2	5	81
0.906482	0.815959	2	19	17	24	1	18	0.3	2	5	14
0.914778	0.82154	2	19	12	27	2	22	0.1	1	5	57
0.915851	0.827163	2	15	20	28	1	16	0.2	1	4	40
0.924289	0.832756	2	20	17	22	2	17	0.3	3	5	60
0.9271	0.84299	2	17	14	27	1	20	0.2	1	4	39
0.931071	0.855449	2	20	15	21	1	23	0.3	2	4	55
0.952662	0.855708	2	20	19	24	2	23	0.2	2	5	85
0.953934	0.857964	2	19	17	29	2	21	0.3	1	5	5

Table 4-33: *Pareto optimal design vectors for the CTA*

	DV	1	2	3	4	5	6	7	8	9	10
Utility	Expense	Conce	Fare	Frequei	Time	Amenit	Span	CCS	Comp Ag	Freedc	CTA cont
0	1	3	10	12	24	2	18	0.3	5	4	100

Table 4-34: *Pareto optimal design vectors for the Private Operator*

	DV	1	2	3	4	5	6	7	8	9	10
Utility	Expense	Conce	Fare	Frequei	Time	Amenit	Span	CCS	Comp Ag	Freedc	CTA con
0.231066	0.123603	2	10	6	21	3	21	0.1	4	4	41
0.231715	0.197203	2	11	9	29	2	20	0.1	2	2	38
0.232036	0.243432	2	18	18	30	1	23	0.1	5	5	14
0.232354	0.352898	2	10	6	21	2	23	0.2	4	4	38
0.233908	0.380667	2	10	15	27	2	23	0.1	2	3	92
0.235407	0.407113	2	16	10	27	1	24	0.1	2	3	96
0.235992	0.455928	2	10	6	21	2	24	0.4	5	3	12
0.237138	0.46746	2	11	10	28	3	24	0.1	2	4	80
0.237701	0.512799	2	13	6	21	1	24	0.1	4	5	53
0.239348	0.517741	2	12	8	26	2	24	0.1	2	3	17
0.242985	0.625093	2	11	8	23	1	21	0.1	4	3	94
0.248675	0.648003	2	10	8	27	1	19	0.1	5	4	15
0.347763	0.69155	1	10	7	20	2	24	0.1	2	4	8
0.434917	0.692553	2	13	8	25	1	23	0.1	4	2	31
0.491811	0.716214	2	11	10	27	2	22	0.1	3	2	58

4.7.6.2 Tradespace for the City of Chicago

Figure 4-14 shows the tradespace for the City of Chicago. The five discrete steps that can be seen for the individual concepts relate to different levels of cost share (10% to 50% in 10% increments). The cost share for the City is a contractual parameter. The discrete steps would disappear if the increment size were to be reduced in a future analysis, for example to 5% or even 1% steps. This would also render the tradespace as a more coherent plot, without visible spikes. The spikes that provide high utility increases at low or no cost increases may surprise. The reason why this is possible is that, for once, the City participates only in the initial investment, consisting of the financing of vehicles and construction cost. The City does not contribute to operating expenditures. That means that designs with higher frequency, or longer span of service, are free for the City, since they do not constitute an expense in the City budget. All optimal designs therefore maximize span of service (24 hour operations) and minimize fares ($5). The City is interested in a large number of riders, and therefore receives higher utility from lower fares. Route 2 is the most expensive design for the City, since it comes at the highest initial expense. BRT is the cheapest option, and BLS is relatively cheap but more expensive than BRT. The optimal designs for the City of Chicago are therefore those BRT designs that have a maximal span of service and a minimal fare. In addition to free increases in utility, the City gains steep utility increases at relatively flat expense increases.

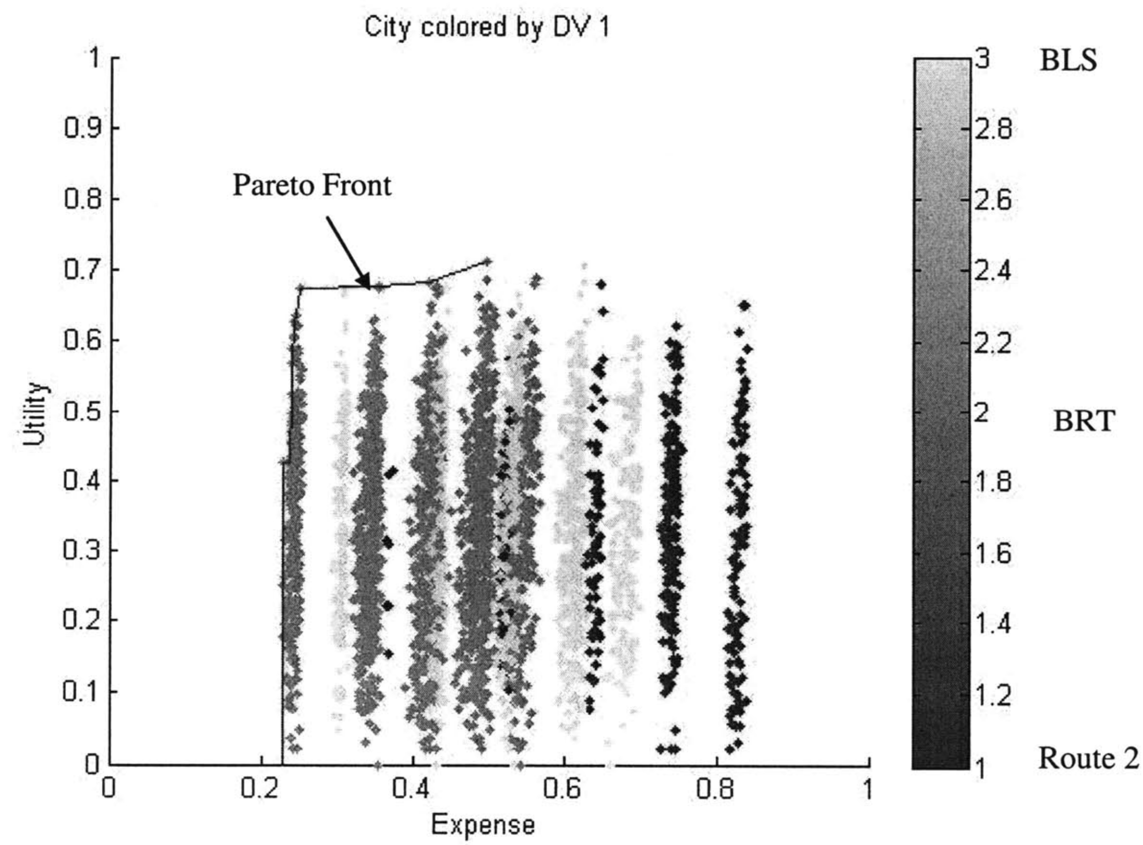


Figure 4-14: *City of Chicago Tradespace, n=20,000*

The reason for the spikes in the tradespace is that the City only bears the initial cost that come with improved frequency. Higher frequency means more vehicles on the route, and therefore more vehicles that need to be purchased initially. The bulk of the cost comes from the increased operating cost, which does not impact the City. It is important to keep in mind that the City tradespace is one tradespace within a multi-stakeholder problem space. A stakeholder can only choose a design in coordination with other stakeholders. A design that is very beneficial for the City of Chicago because it requires little financial contribution will require a larger contribution from other stakeholders. The very beneficial outcomes for the City (high level of service, minimal financial contribution) will likely not be chosen in an actual negotiation setting with a (somewhat) balanced power distribution. All Pareto optimal designs are of the architecture concept BRT.

4.7.6.3 Tradespace for the CTA

Figure 4-15 shows the tradespace for the CTA.

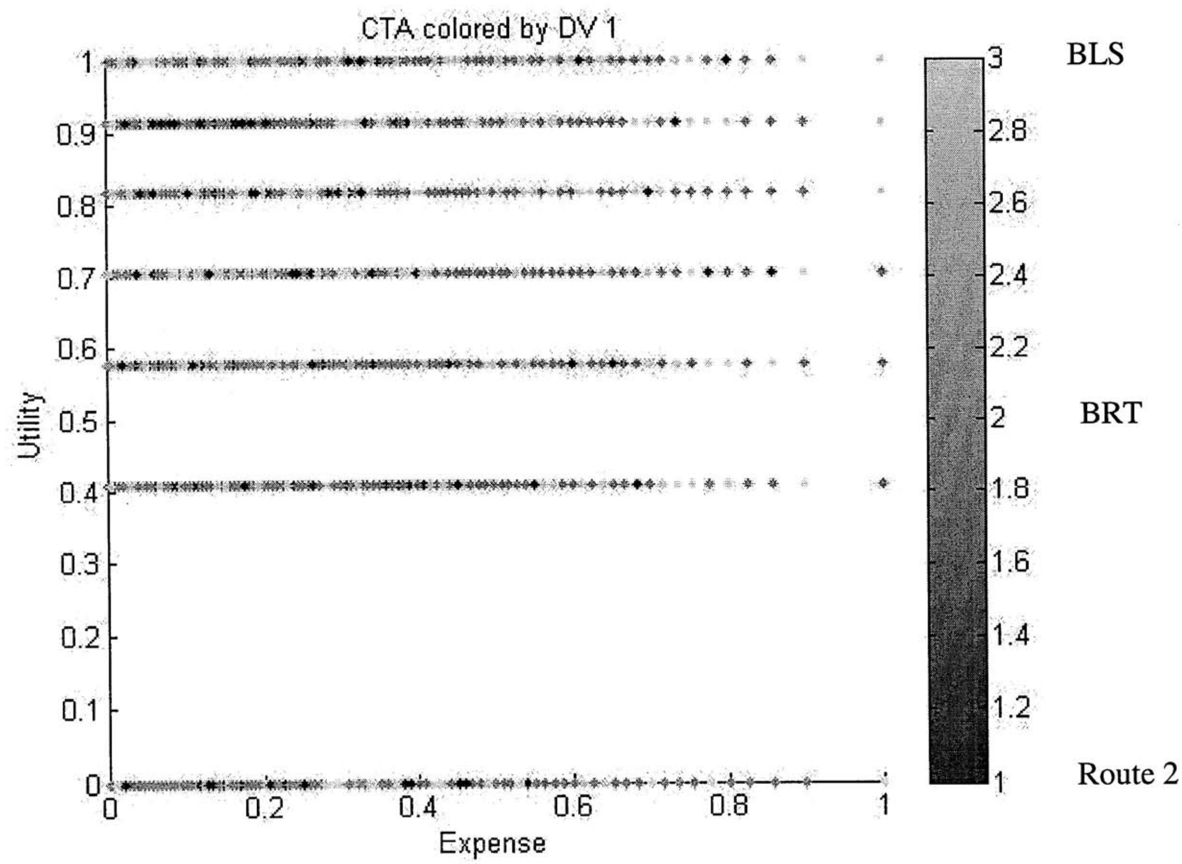


Figure 4-15: *CTA Tradespace, n=20,000*

A major concern at the CTA is to not inconvenience current Blue Line riders through joint operation of the Blue Line and the airport express on shared tracks. After ruling out the only architecture concept (Route 1) in which this condition would have appeared, two attributes remain that are able to differentiate between different designs: one benefit (maintainability, which is the opposite of service span or the number of hours during which tracks could be maintained), and one cost (CTA initial cost). Since CTA initial cost contribution and span of service are independent of each other (span of service only drives operating cost, but not initial cost), the attributes are decoupled. The resulting tradespace is therefore very simple.

Utility corresponds to the number of hours that would be available for maintenance per day. Every additional hour increases utility (discretely in this model), whereas expense increases depending on the required contribution to initial cost by the CTA. The Pareto Set for the CTA includes the three designs with values for DV6 and DV10 of (0, 16), (0, 17) and (0, 18). In actual units those designs represent those that call for $0 contribution to initial costs by the CTA and allow for 16, 17 or 18 hours of service per day, leaving at least 6 hours for undisrupted track maintenance per day. Those design vectors fall together on the Pareto Front (e=0, u=1). Since the Pareto Front consists of a single point, it is not indicated. The CTA has the highest utility if it does not need to contribute to the initial costs, and if it has at least 6 hours without operations available per day in which maintenance can be performed.

4.7.6.4 Tradespace for the Private Operator

The tradespace for the Private Operator has a shape that indicates diminishing utility returns on increased expenses. BRT clearly emerges as the dominant design, since all Pareto optimal designs share this design concept (DV 1). The yield for BLS (yellow) is smaller and very small for Route 2 (red). Expense has relatively high fixed part, since Operating Costs need to be born in full by the Private Operator in any case, with some variation depending on the chosen concept.

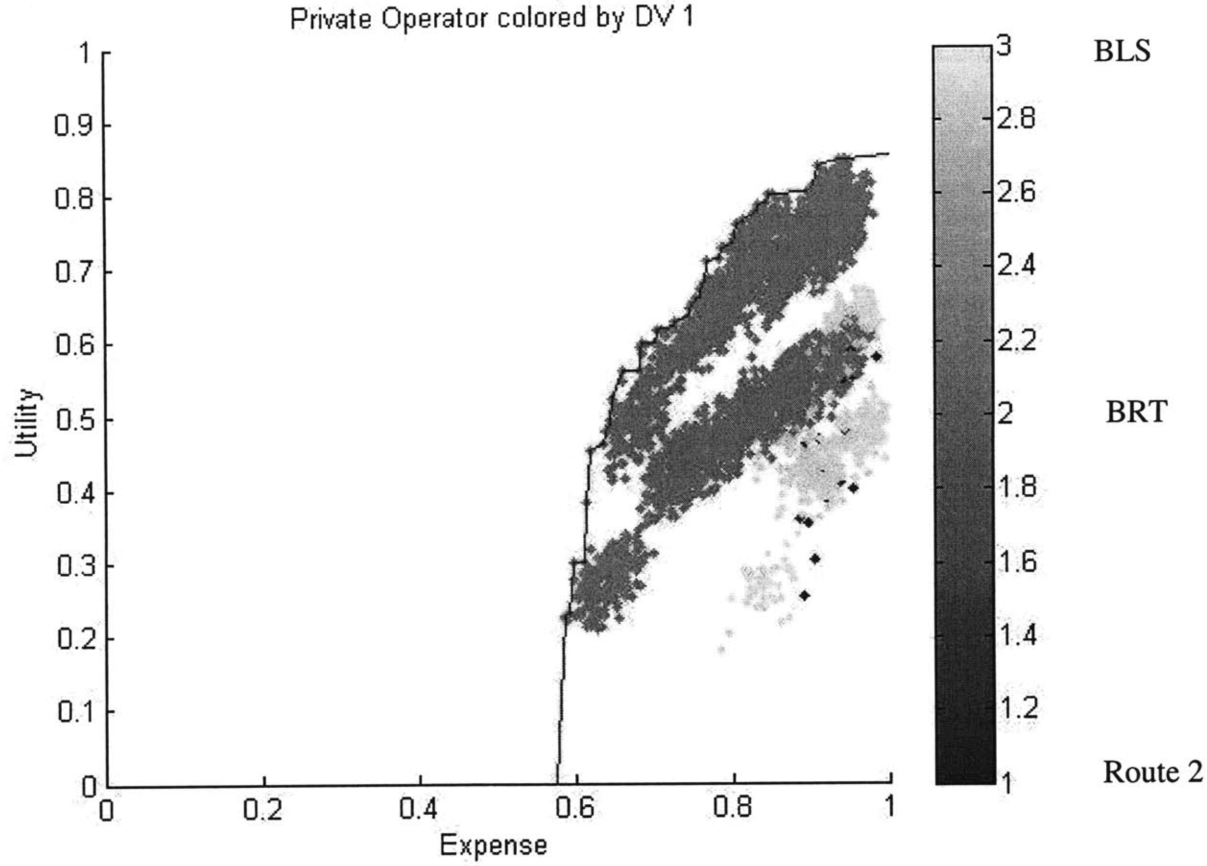


Figure 4-16: *Tradespace for Private Operator, n=20,000*

4.8 Tradespace Exploration

A full tradespace exploration would address additional questions. Of particular interest is a plot that shows the goodness of stakeholders' Pareto optimal designs in each others' tradespaces (in the quest for promising compromise designs) and a sensitivity analysis on operating costs and the shape of utility and expense functions as well as the swing weights k_i..

Questions for full tradespace exploration:

0. Does the tradespace make sense? The plots to answer this question are provided in Appendix 7.8. Tradespaces are plotted for all design variables that show patterns.

1. Can we find good value designs? Compromise designs? What do we give up to find these? How do Pareto optimal designs appear to other stakeholders?

2. Can we find designs that satisfy multiple stakeholders? What compromises need to be made?

3. What are the strengths/weaknesses of selected designs?

4. Are lower cost designs feasible? What sort of compromise need to be made to lower cost?

5. Do closer looks at the designs and more advanced visualizations support our conclusions?

4.9 Determine "best" alternatives

The results of the CBA indicate that BRT is the only architecture concept that provides net benefits to society independent of the discount rate. Route 2 has the highest net benefits at a discount rate of 7%, indicating that there are higher initial expenses and larger future benefits. Depending on how strongly future benefits are discounted, this option proves either advantageous or not advantageous. The Blue Line Switch option is inferior independent of discount rate. If a low government discount rate is used, both BRT and Route 2 can be justified with a CBA. CBA is however only one method in a suite of methods that are used to explore the impacts of a technical design. The decision also needs to be informed by financial analysis. BRT is a recommendable solution if one wants to ensure net benefits according to CBA that is robust against changes in the discount rate.

In the tradespace analysis, BRT emerges as the single best architecture concept for the Private Operator and the City of Chicago. The tradespace of the CTA is not particularly helpful in selecting a design, since both attributes are independent of each other. The tradespace fits into the overall image that the CTA conveyed during the interviews: the CTA will most likely not have any financial gain from the airport express, but be merely the contractor that maintains the tracks and operates the trains in return for a contractually fixed payment. As such, the CTA is trying to minimize potential disadvantages to current operations and to their financial ability. None of the CTA attributes indicate a preference for a particular design, except that it not be Route 1 (which had been eliminated). The preferences of the City of Chicago are driven by low initial costs, since the City would only need to bear a share of the initial expenditure. This leads to a preference of BRT over the other designs. The City also favors more frequent and longer operations (longer span of service), since those operations provide benefits which the City would not need to pay. Apart from those fundamental patterns, utility increases with increased investments in service design variables.

BRT emerges as the dominant design from the MATE analysis. Repeating the calculation with a larger randomly sampled design space (current size n=20,000) would be needed to gain confidence in this result.

Because of the significantly lower cost of BRT and robustness against changing discount rates, it is much more likely to reach a consensus among the stakeholders. Based on the analyses in this chapter so far, BRT is recommended for further study.

4.10 Discussion and evaluation of "shortcomings" of CBA in this case

One criticism of CBA is the fact that it performs inter-personal utility comparisons, that is, it aggregates the utility of different stakeholders to a single number. In this example, CBA demonstrated that the airport express has potential to save a substantial amount of travel time for users of the airport express and car drivers on the Kennedy Expressway through relieved congestion. The inner dynamics of interests between different decision-making stakeholders however remain hidden. Even though Economic Impact Analysis as an additional method tends to shed more light on the distribution of costs and benefits through revelation of likely gains in travel time, land value, visitors, for example, of certain areas, this analysis does not apply to the personal interests of involved decision-making stakeholders.

In fact, even this example analysis for demonstrative purposes has already revealed several patterns of preferences and interests that will be most interesting for all stakeholders in actual negotiations. The CTA has not much to gain and tries to minimize their losses. The City is in a situation in which it is only responsible for contributing to the initial investment, but not to operating expenses (this prediction assumes operating self-sufficiency, as is the result from several studies under conservative estimates). This political and regulatory fact has a major influence on design selection, independent of technical considerations. The Private Operator is less interested in the public good and more in Return on Investment. Whereas the City values the number of riders attracted to downtown, with the price they are paying on the airport express being a lesser concern, the Private Operator cares about profit maximization. Interestingly, the Private Operator cares about a number of attributes that do not have a monetary equivalent, such as freedom to make operative changes without consulting other stakeholders or competition agreements. These attributes were not expressed by the CTA or the City of Chicago. Depending on their preferences when these points are brought up in discussion, there may be a possibility to trade in a higher concession contribution by the Private Operator in return for concessions on these non-monetary attributes. It is questionable if and to what extent these details would have been revealed in a traditional project evaluation process. By revealing this information, MATE can constitute a valuable additional tool in project evaluation to help mitigate the ignorance of the distribution of costs and benefits and add consideration for non-monetary costs and benefits. In this way, MATE contributes to better accounting for the hard-to-come by "evaluative complexity" in project appraisal, which ultimately has to be resolved in negotiations.

Even though CBA showed that travel time savings can be substantial through the proposed project, the evaluation is skewed through the practice of discounting these non-monetary benefits. Whereas discounting makes sense for financial assets, the equivalent logic does not easily apply to the discounting of future travel time savings or future emissions. Even if the quantification into monetary values can be justified, it is hard to justify why the time of people today should be more valuable than the time of their children. The project evaluation of the option Route 2 shows how much power the discount rate has over making the same project either look beneficial or undesirable, solely based on how steeply future benefits are discounted.

In addition, several non-monetary costs such as emissions are quantified through a linear model in this paper. In reality however, harm from emissions is non-linear. MATE allows for the accounting of this type of information (to be elicited from climate experts), which may be gathered from experts during the evaluation process. There is a danger that certain types of "soft" benefits, such as diffuse benefits to the community or environmental harm/benefits are not perceived as urgent causes by decision making stakeholders. A possible strategy to avoid this effect is to capture potential unarticulated attributes either through a proxy stakeholder (for example, "environmental stakeholder") or in the form of unarticulated attributes (this is part of Dynamic MATE and is discussed in the next section).

The flexibility in capturing attributes, things that people are interested in, permits accounting for programmatic attributes. In this thesis, the compared designs had relatively short project completion schedules of about 2 years after start of construction. Other designs for the construction of new rail tracks that were discussed in technical reports (and deemed inferior to Route 2) however, involved more construction work and a longer project completion phase. In evaluating these designs, an attribute for the likelihood of project completion before a certain deadline (e.g., 2016 for the Summer Olympics) can be introduced. Due to the selected designs, however, this shortcoming was of lesser concern in the demonstrated analysis in this chapter.

Another critique of CBA is the fact that initial investments and operating costs (often far into the future) are discounted and aggregated to a common value. The case can be made that (relatively) certain expenses today and uncertain future costs or revenues tomorrow constitute different "colors of money." The analysis demonstrated how MATE can account for different cost types. In the case of the Private Operator, operating costs and construction costs were kept separate and evaluated differently. For further analysis, it is possible to separate the costs and display them individually against the aggregate utility of different designs. This possibility for further exploration of the impact of different costs (including different "colors of money" and non-monetary costs) is another potential for additional insight that can be gained through the use of MATE.

4.11 Discussion of political feasibility and potential opposition

The MATE and CBA analyses took into account attributes that decision making proxy stakeholders expressed or that guidelines for CBA suggested. BRT emerged as the superior concepts, while the Blue Line Switch Concept and Route 2 were dominated. In this section, additional considerations for implementation and political feasibility of all three concepts are addressed qualitatively. Likely support and opposition from different stakeholder groups as well as potential mitigation strategies are discussed. This section concludes the case study by pointing out important aspects that need to be kept in mind and that can serve as suggestions for stakeholder attributes (possibly unarticulated) in future MATE studies in the transportation domain. The discussion fortifies the result that BRT is recommended for more serious study towards implementation. It should be kept in mind that of the discussed architecture concepts, only Route 2 was part of the original technical studies.

Dedicated BRT lane

The discussion about capacity reduction on the Kennedy Expressway in section 4.6 showed that the rapid transit bus will likely offset the capacity reduction if one lane in each direction were to be dedicated to BRT. Average car travel speeds would then not be impacted. Despite this prognosis, underused capacity on the BRT lane would be a political problem. At 74 runs per day in each direction, capacity on the separated bus lane would be underused and hence not lead to an efficient use of resources. Car drivers would see a bus pass by every 10 minutes and become angry, possibly while dragging in traffic on one of the other four lanes of the Expressway. To mitigate opposition from commuters and use resources efficiently, the separate BRT lane may be opened up to commuters against payment of a toll. Congestion leads to welfare losses through waiting time, and a large body of economic literature argues that congestion tolling can be used to regulate traffic flow and achieve optimal throughput levels. In this situation the payment of a toll would be optional for people who are in a hurry, while whoever is opposed could still use one of the other four lanes. The competitive advantage of the buses would be lost to some extent, but the toll and an additional airport fee for taxis may help prevent cannibalization of the airport bus through limiting the number of cars on the tolled road.

Employment generation and job losses

Employment benefits from the Blue Line Switch option are complicated to evaluate. Shutting down the Blue Line reduces jobs, whereas the new bus system creates jobs. These jobs cannot be easily substituted for each other: more drivers are needed for the bus operations, but more mechanics are typically needed for Heavy Rail and track maintenance than for BRT. As a rule of thumb, one heavy-rail-car employs 4.6 people, including driver, mechanics, janitors and management. A local bus employs 2.6 people (lecture notes from MIT course ESD.225), and BRT will employ a little bit more than regular bus for being more complicated technically, possibly around the order of 3 people.

Very roughly estimated from the number of train cars and buses required to provide Blue Line service, the difference in number of mechanics needed between heavy rail and BRT is on the order of 50 people. Around 120 net new bus driver jobs will be created in the Blue Line switch option. Despite the net increase in jobs by 70, employees and unions will protest if 50 mechanics would either lose their job or be forced to become bus drivers, which many of them won't accept. In addition, the CTA would incur retraining costs for several hundred employees who need to be retrained from being a train operator to being a bus operator, and more difficultly, from train mechanic to bus mechanic (assuming this is possible and employees agree to the change). The situation could potentially cause a big political problem around the Blue Line Switch Option, involving bad publicity.

Mitigation payments to these workers would possibly increase total project costs on the order of several million dollars. Additional solutions would have to be found for how to deal with these people's pension claims.

Dispersion of investment

Operating costs for electricity would remain in the City of Chicago, whereas both expenses for vehicles and fuel for BRT and the Blue Line switch option would leave the state of Illinois. This argument may be advanced by opponents to the Blue Line Switch Option, which requires the largest investment in new vehicles and fuel. Theoretically, the argument can also be made for BRT. Buses are however manufactured in the neighboring city Detroit, MI; which would still have the effect of securing political goodwill from the State of Michigan and potentially the Federal Government. These considerations carry more weight depending on the agenda for regional economic stimuli that the project has presently and in the future. They are an example for an attribute that may change in importance over time, depending on the economic situation.

Uncertainty and Scalability of operations

Uncertainties that are related to this project include ridership development, enplanements at O'Hare, mix of airport express riders from former transit and car users, and diesel and electricity prices. The airline industry is traditionally a highly cyclical industry, which has not been represented in the CTA estimates. An airport express concept with lower capital costs and higher operating costs allows a better response to this changing demand pattern. BRT and the Blue Line switch option are advantageous from this point of view, since scaling back of operations in times when demand is slow has the greatest impact on cost savings when variable costs are high. Through the lower capital costs for BRT (no maintenance of right of way, less capital for rolling stock), capacity can more easily be added if demand supersedes projections. Uncertainty about future diesel prices is a major concern at the CTA. Sensitivity analysis and further study should evaluate the potential benefits of investments into hybrid buses.

4.12 Recommendation for the City of Chicago

Overall, Bus Rapid Transit emerges as the best design option from a political feasibility point of view. Capital expenditure for BRT is low enough for the CTA and the City of Chicago to self-finance this option, making them independent from the concession payment of a Private Operator. Without the need for a financial contribution, it will be easier to find a private party to manage operations since the likelihood is greater that a single party would be able to do so at a profit.

The major caveats of BRT are the political will required to dedicate one lane of the Kennedy Expressway to BRT, and prestige concerns. To secure political will for a BRT lane separation, the separated lane could be opened up to other cars against payment of a toll. Since the BRT airport express would only run every ten minutes, a lot of capacity on the dedicated bus lane would be underused. Tolls need to be collected on ramps before entering the fast lane, so as not to slow down buses. This initiative can be explained to the public as offering a possibility for people who need to make urgent appointments to do so for a fee. Those who are opposed are free to use any of the other four expressway lanes.

Prestige concerns with airport travelers can be addressed by marketing campaigns at O'Hare, clearly conveying that BRT is the fastest and most reliable travel option to downtown. Luxurious amenities like air-conditioning, space and power outlets for laptops change the look-and-feel of a bus and make it appear more special. Even if BRT might not be preferred by airport travelers if a train was available, it may very well be possible to convince them that it is their best available option. An investment into hybrid buses can be used to lessen dependence on fuel and give the airport express a greener image, while reducing emissions. To put the discussion about the negative image of BRT on a more objective basis, interviews at O'Hare should shed light on the true preferences of the targeted customers.

The next chapter discusses the application of MATE and CBA to a mixed passenger-freight transportation problem within the institutional setting of Portugal in Europe.

Chapter 5 Case study 2: Portuguese High Speed Rail (Set-up)

5.1 Approach

This chapter describes the set-up of a MATE application to a more complex transportation design problem: a high speed mixed passenger-cargo rail connecting Lisbon, Portugal to Madrid, Spain. Before discussing the project evaluation using both MATE and CBA past and present conditions (institutional, technical) of this non-US design problem are reviewed. The chapter seeks to explore what insights a MATE analysis could provide in comparison to CBA. Comparing both methods within a second case study provides additional insights into how both methods could be used together, which is discussed in Chapter 6.

The focus of this case study is on a High-Speed Rail (HSR) axis between the Portuguese capital of Lisbon and the Spanish capital of Madrid. Modeling approaches are discussed, but no complete parametric models are presented that would allow the creation of a tradespace. This chapter begins with (5.1) this description of the approach and (5.2) an introduction to HSR and transportation in general in Portugal, (5.3) identification of the mission statement and stakeholders of the design problem along with attributes and epoch variables for a MATE analysis. Section (5.4) refers to a professionally conducted CBA about the Lisbon-Madrid corridor. Section (5.5) discusses design variables and architecture concepts for a MATE study. Section (5.6) discusses next steps that would be required for tradespace generation and (5.7) concludes with a discussion of insights gained from CBA and MATE in this case study.

5.2 Introduction

Currently no HSR network exists in Portugal and the existing conventional rail network has several shortcomings, including one-track and indirect connections between important areas of Portugal and Spain. The two main axes of the proposed high speed rail network are Lisbon-Madrid and Lisbon-Porto. Among the benefits that the construction of an HSR network is expected to deliver to Portugal are

- capacity expansion of the current congested transportation infrastructure (road and air);
- reduction of the geographical isolation of the country within Europe through improved transfer of passengers and freight between economically vital areas in Portugal and the rest of Europe;
- improvement of cohesion and quality of life in Portugal;

- improvement of European access to Portuguese ports to enhance their role as cargo hubs;
- economic stimulation both directly from the construction activity and indirectly through agglomeration benefits and improved infrastructure; and
- reduction of the external costs of transportation (emissions, noise, etc) in Portugal.

The case study presented in this chapter concentrates on the axis between Lisbon and Madrid, with a possible link from Evora to the important seaport of Sines.

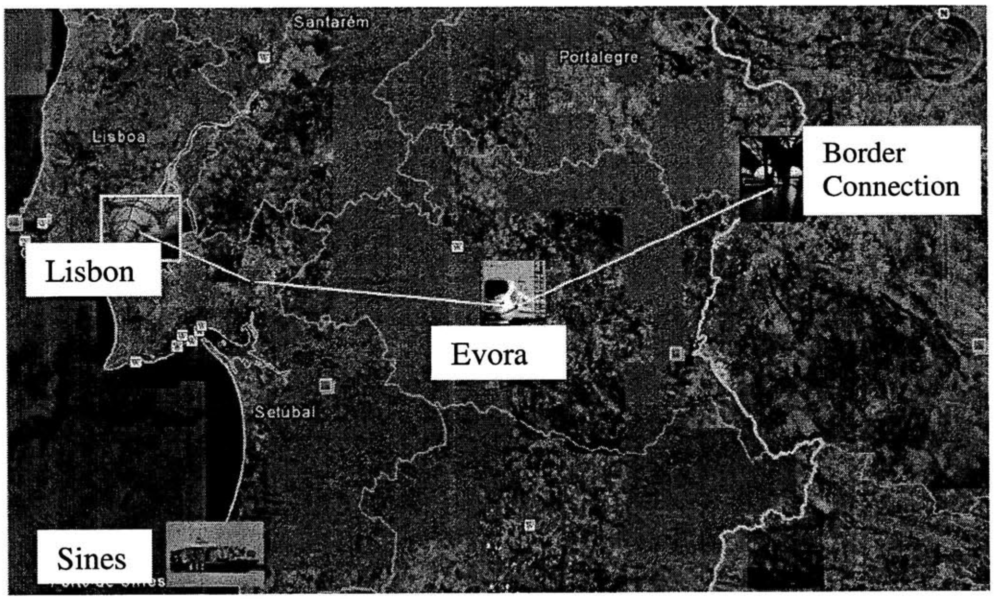


Figure 5-1: *Lisbon- Spanish border HSR links. (Google Maps 2009)*

5.2.1 High Speed Rail (HSR) in Europe

HSR is a technology for passenger transportation that achieves significantly higher maximum speeds than conventional rail systems. The European Union defines "high speed" for trains as a speed higher than 200 km/h (125 mph). Most HSR systems are electrically driven via overhead lines, but other forms of propulsion, such as diesel locomotives, may be used also. A definitive aspect is the use of continuous welded rail in order to reduce track vibrations. Well developed high speed rail networks exist in several European countries, including major industrial cities in Germany, France, Great Britain, the Netherlands and Spain. Figure 5-2 illustrates the existing HSR network in Europe and the planned network in Portugal. Figure 5-3 and Figure 5-4 show examples of world-renowned HSR systems in France and Japan. The Iberian Peninsula currently possesses two HSR corridors in Spain, linking Madrid to Barcelona in the west and Madrid to

Malaga in the south. In the European context, Portugal is a relatively late entrant into the HSR realm.

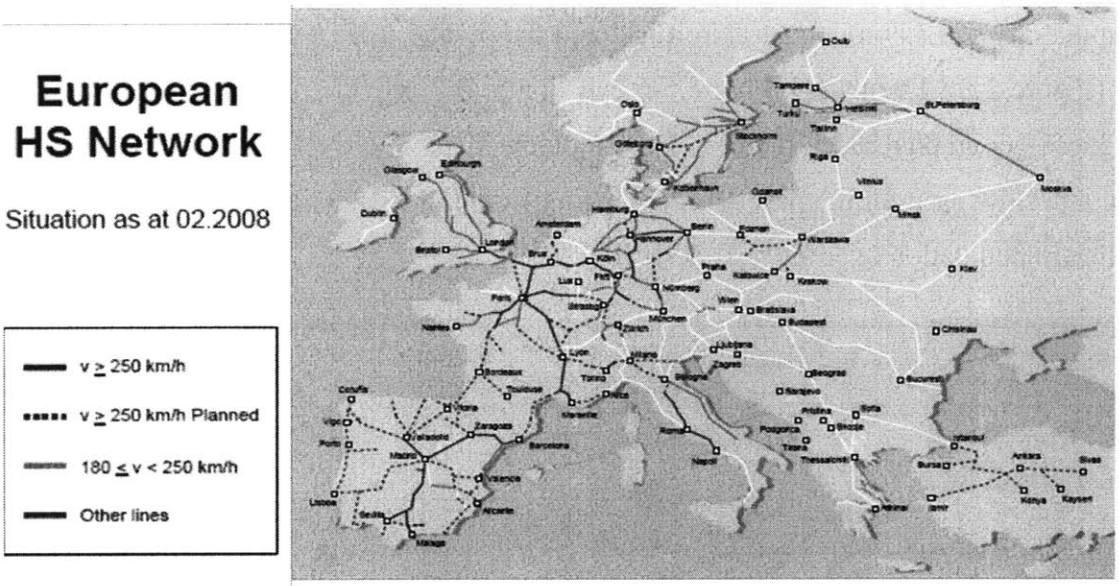


Figure 5-2: *European HSR Network as of 02/2008. (RAVE 2009)*[22]

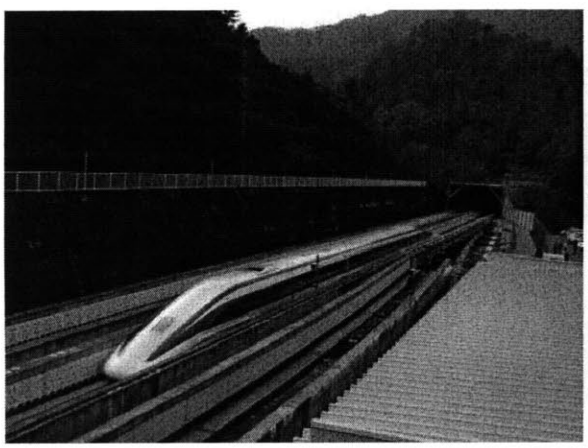


Figure 5-4: *Japanese Shinkansen (Wikipedia 2008)*

Figure 5-3: *French TGV (Wikipedia 2008)*

The state-owned enterprise RAVE (Rede de Alta Velocidade) has been tasked with the development and implementation of efforts to create an HSR network in Portugal.

[22] Retrieved 12/20/2009, from http://www.rave.pt/tabid/372/Default.aspx.

5.2.2 Background information on Portuguese geography and economy

Located on the westernmost edge of Europe, Portugal is home to 10.6 million residents. Approximately 70% of the country's population is concentrated in the coastal corridor between the capital city of Lisbon in central Portugal and the second-largest city of Porto in the country's north (Figure 5-8). Figure 5-5, Figure 5-6 and Figure 5-7 provide further information about the Portuguese geography and a picture of the national flag. The total population of Portugal has grown at a slow pace for the past decade, ranging from 0.2 to 0.8% annually. Forecasters project a decline in population over the next 20 years.

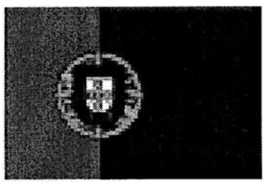


Figure 5-5: *Portuguese Flag (CIA World Factbook 2010)*

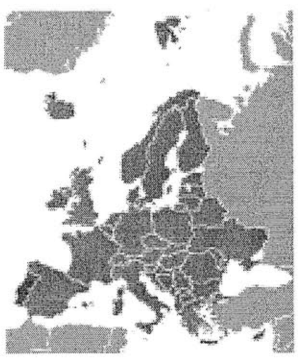


Figure 5-6: *Portugal's location in Europe (CIA World Factbook 2010)*

Figure 5-7: *Map of Portugal (CIA World Factbook 2010)*

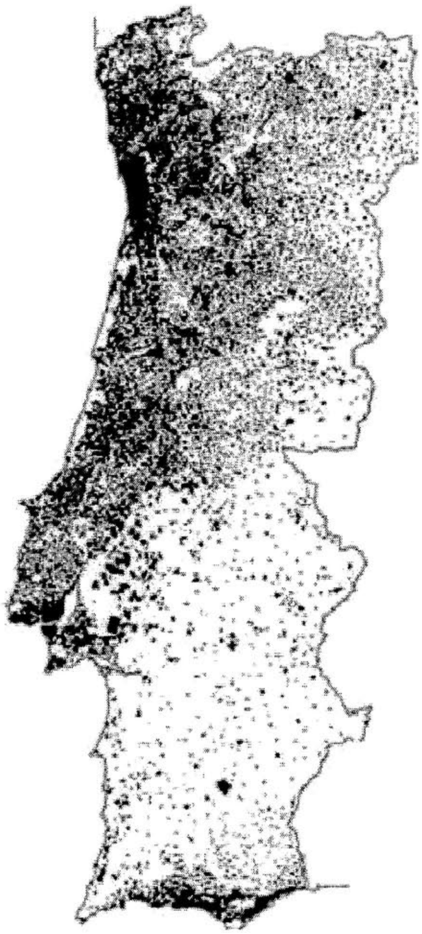


Figure 5-8: *Population distribution in Portugal (MOPTC, cited after (Dunn 2009))*

The following description is based on information about Portugal available online in the (CIA Factbook). After Portugal's Golden Age as a global sea power in the 15^{th} and 16^{th} centuries it lost much of its status during the coming centuries due to the destruction of Lisbon in a 1755 earthquake, occupation during the Napoleonic Wars, independence of its wealthiest colony of Brazil in 1822, and a series of repressive governments in the 20^{th} century.

Today, Portugal occupies an area of 92,000 km^2, which is slightly smaller than the US state of Indiana. It possesses 1,214 km of border line with Spain and 1,793 km of coast line to the Atlantic Ocean. The climate is maritime, with a cooler rainier climate in the north and a drier, more humid climate in the south. Arable land, fish, forests, and hydropower as well as minerals are the country's natural resources. Natural hazards are not a big threat to mainland Portugal, but the country feels the threat to its natural resources from environmental hazards: soil erosion, air pollution (caused by industrial and vehicle emissions) and water pollution, especially in coastal areas.

The CIA Factbook describes the economic situation in Portugal as follows:

> Portugal has become a diversified and increasingly service-based economy since joining the European Community in 1986. Over the past two decades, successive governments have privatized many state-controlled firms and liberalized key areas of the economy, including the financial and telecommunications sectors. Economic growth had been above the EU average for much of the 1990s, but fell back in 2001-08. GDP per capita stands at roughly two-thirds of the EU-27 average. A poor educational system, in particular, has been an obstacle to greater productivity and growth. Portugal has been increasingly overshadowed by lower-cost producers in Central Europe and Asia as targets for foreign direct investment. The budget deficit surged to an all-time high of 6% of GDP in 2005, but the government reduced the deficit to 2.6% in 2007 - a year ahead of Portugal's targeted schedule. Nonetheless, the government faces tough choices in its attempts to boost the economy, which grew by 0.9% in 2008, while keeping the budget deficit within the Euro zone 3%-of-GDP ceiling.

(CIA World Factbook 2010)

The estimated GDP for Portugal is $237.3B (2008), or $22,817 per capita. When accounting for Purchasing Power Parity, GDP is estimated at $255.5B (2008, both estimates expressed in 2008 $US). Portugal's nearest neighbor, Spain, had an estimated 2008 GDP of $1.4 trillion, or $34,000 per capita. By comparison, the US GDP was $14.6 trillion for 2008 ($48,000 per capita). The unemployment rate in Portugal is at 7.6%, and 18% of the population lived below the poverty line in 2006. The poverty line is a measure determined by the World Bank and is calculated in relation to the national GDP. The national Portuguese budget accounted for $108.6B in 2008. Expenditures during the same year were projected at $114.7B, further deepening the public deficit. Public dept was around 64.2% of GDP in 2008, ranking Portugal as number 19 in the world's listing of states with the highest public deficits. Runners up in the same ranking were Germany, Canada and the United States on positions 20, 21 and 22. The country's external debt was $461.2B as reported on December 31, 2007.

The following summary in this section is closely based on a presentation and teaching notes delivered by Doctoral student Travis Dunn to the students in course ESD.01, "Systems Engineering Design", taught by Prof. Sussman at MIT in the Spring of 2009 (Dunn 2009).

The principal economic activities in Portugal include services such as software and telecommunications and manufacturing such as automobiles, auto parts, chemicals, metals, textiles, ceramics, ships, and ship repair. Most of the plants are clustered between Lisbon and Porto, focused on the key export markets of Spain, France, and Germany, with most manufacturing activities occurring in urban areas. Although many key sectors of the Portuguese economy have been opened to competition, such as banking, communications, and transportation, the state still owns many of the major companies in these industries and in fact controls nearly half of the GDP (for comparison, the US federal government controls less than 20% of US GDP, with revenues and expenditures between $2.5-3 trillion out of a total GDP of $14.6 trillion).

Portugal acceded to the EU in 1986. Despite some regulatory institutions, the EU's most important role as measured by expenditures is to provide for economic development and cohesion of its member states, mainly through distributing funds to specific sectors of the economy (e.g., agriculture and transportation) and to specific regions (e.g., Central and Eastern European countries) in need of economic development. The proposed HSR project in Portugal may receive EU funding for the reasons of promoting internal cohesion and economic development. Portugal enjoyed an influx of development funds from the EU in the 1980s and 1990s. With a new inward focus, the government devoted these funds to the modernization of infrastructure, including telecommunications and transportation (Dunn 2009). In the 2000s, however, the country entered a period of financial and economic instability. Portugal's government deficit in 2005 reached 6% of GDP, exceeding the EU-enforced limit of 3%. The government was able to reduce the deficit to 2.6% of GDP by 2007, but unemployment remains high and GDP growth low. Further threats to Portugal's near-term economic viability include competition from the low-cost labor markets of Central Europe, Eastern Europe, and Asia; declining population; and a weak educational system.

5.2.3 Intercity Transportation in Portugal

Portugal has an extensive, modern road network consisting of over 17,000 kilometers of intercity roadways, complemented by an additional 90,000 kilometers of municipal roadways. A major international airport in Lisbon (Portela) serves the majority of air passengers. A secondary and tertiary airport in Porto and Faro serve mainly domestic and seasonal touristic demand. Portela in Lisbon serviced 12 million passengers in 2006 and is working at capacity. The airport, however, cannot be expanded to provide the needed additional capacity since it is located in a densely populated area close to the city of Lisbon. In reaction to pressure since the early 90s, the Portuguese government decided to build a second airport to provide additional capacity in the Portuguese aviation system. Discussions about the siting of this airport have been going on for many years.

Portugal's conventional rail network spans 2800 km and connects 650 station stops, serving primarily passengers. The conventional rail network in Portugal shares a common (Iberian) gauge with Spain, but is not interchangeable with the rest of Europe, which operates smaller standard gauge rail networks. Eighty percent of domestic intercity traffic in Portugal is road traffic. Important sea ports are located in Leixoes, Lisbon, Setubal, and Sines. The central Portuguese government is the principal entity responsible for the maintenance and operation of transportation infrastructure and services in Portugal. The organizational structure of the Portuguese transportation sector is displayed in Figure 5-9. The key bodies in the transportation domain in Portugal are ministries (equivalent to US departments), regulatory agencies, state-owned enterprises, and private concessionaires.

Table 5-1: *Acronyms in Figure 5-9*

MOPTC	Ministry of Public Works, Transportation and Communication
MFAP	Ministry of Finance and Public Administration
InIR	National Roadway Infrastructure Institute
INAC	National Institute for Civil Aviation
IMTT	Institute for Surface Transportation and Mobility
EP	Portuguese Highway Management (Maintenance)
TAP	Portuguese National Airline
ANA	National Airport Authority of Portugal
STCP	Municipal Porto Transit Authority
CP	Portuguese Standard Rail Network Operator
REFER	National Railway Network (Standard Rail Maintenance)
RAVE	Planning body for HSR network
SEE	Government body managing Portuguese public companies
MST	Subway operator in area south of the river Tagus

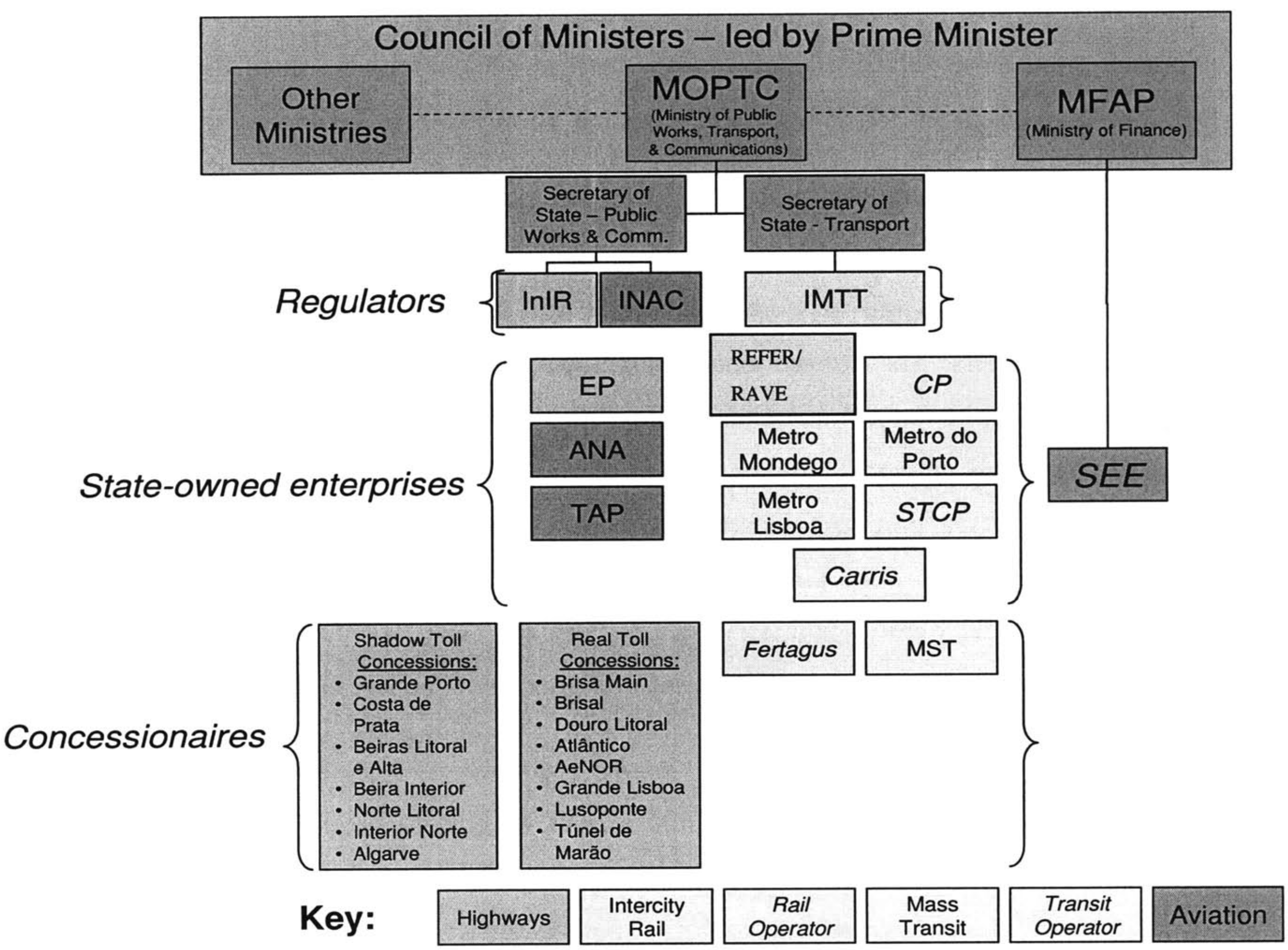


Figure 5-9: *Hierarchy of Portuguese Transportation Organizations (MOPTC, cited after (Dunn 2009))*

5.2.4 HSR in Portugal: Example of a planning process

The planning process of HSR in Portugal goes 10 years back. Table 5-2 serves as an example outline for the iterative decision making process in transportation planning. Typical elements are memoranda of understanding, preparation of a master plan, business and procurement models, a CBA as part of a funding application (here: application to European Union Ten-T Multi-Annual Work Program 2007-2013), EIS and design studies, iterative exploration and decision making on key design questions (mixed passenger/ freight operations, location of Lisbon station), and a tender for a Public Private Partnership. Planning processes of other transportation projects may not include certain elements if not applicable (e.g., tender for public private partnership), and may include a slightly difference sequence of steps. RAVE was created in December of 2000 with the task of administering the planning, tendering process and construction of an HSR network in Portugal. Since the planning effort requires extensive co-ordination with the Spanish side, a separate entity, AVEP, was constituted in January of 2001 with the task of coordinating interactions with the Spanish agencies. Table 5-2 highlights milestones of the project until June of 2008. Important milestones were the decision for mixed passenger and freight operations (November of 2005) and the launch of the first Public Private Partnership tender in June of 2008.

Table 5-2: *Milestones in Portuguese HSR planning effort (Lisbon-Madrid axis, 2008 RAVE Report (RAVE 2009))*

Date	Milestone
Dec. 2000	Creation of RAVE
Jan. 2001	Creation of Spanish-Portuguese HSR co-ordination entity for the development of all cross-border axes between the two countries (AVEP)
Nov. 2003	Portugal – Spain Summit: Memorandum of understanding was signed defining:
	- HSR cross-border axis - Journey time targets
Apr. 2004	Lisbon- Porto, Lisbon- Madrid, Aveiro – Salamanca and Porto – Vigo included in a program called *Ten-T Priority Projects*
Nov. 2005	Portugal – Spain Summit: Memorandum of understanding signed regarding the Lisbon – Madrid HSR Line
	- Mixed Traffic desired– passenger and freight - Definition of completion dates
Dec. 2005	Public project announcement
	- Priority links defined (Lisbon – Madrid and Lisbon – Porto)

Jun 2007	Public project announcement: - Business and Procurement Model - Master plan 2007/2011 - Preventive measures approved by the Portuguese Government for the Lisbon-Madrid axis
Jul 2007	- Submission of applications for the Ten-T Multi-Annual Work Program 2007-2013 (program of which Lisbon-Madrid axis is part) - Common declaration signed between Portugal and Spain for the coordination of the works on the cross border sections
Aug 2007	Completion of design studies and delivery of Environmental Impact Studies for the Lisbon-Madrid HSR line
Dec 2007	Final decision on the location of Lisbon central station
May 2008	Completion of the Environmental Impact Assessment Procedure for Poceirão- Caia stretch of the Lisbon-Madrid HS line
Jun 2008	Launch of the first Public Private Partnership tender for the HSR Infrastructure for the Lisbon-Madrid HS Line (Poceirão- Caia stretch)

5.2.5 State-owned enterprises in Portugal

Because state-owned enterprises are an integral part of the Portuguese transportation system, a brief introduction to their purpose and functioning is presented in this section.

Industries that exhibit natural monopolies, such as public utilities, coal, steel, transportation, or banking, have historically often been regulated by the government. A common instrument for state intervention is the state-owned enterprise (SOE). State regulation of market dynamics has been justified in different ways. According to (Bös 1986, cited after (Flores-Macias 2008)), SOEs provide goods and services "that cannot be cut off without danger of total or partial collapse of an economy". The industries which they control are often strategically important to the functioning of a state or a society. From an employment perspective, SOEs "can afford the luxury of not firing workers during economic recessions, thus mitigating the impact of business cycles via de facto unemployment insurance" ((Flores-Macias 2008). Through the 80s and 90s public companies were viewed with increasing skepticism, as they became associated with "excess employment, corruption, and massive subsidies" ((Flores-Macias 2008). During the same time many industrial sectors saw an era of privatization, such as the airline industry worldwide and the national rail systems in Great Britain and Germany as examples from the transportation sector. Compared to other countries, Portugal has a very strong tradition of government involvement in the national transportation industry (with the exception of private tolled highways). This ownership structure has important implications for the way the transportation enterprises operate. For a public company it is possible to operate at a loss if the government deems its service sufficiently important for the country. Sufficient importance can for example be established if the enterprise provides significant non-monetary benefits to the population or the environment, such as enabling trips to work, linking businesses through the provision of transportation infrastructure, or by reducing external costs to the environment. Investments and services do not require a positive NPV in a financial analysis to be feasible, but funding must be available from other sources such as subsidies or loans.

Article 4, Diário da República, (Decreto-Lei nº 558/99 de 17-12-1999, Chapter III), states the two goals of a balanced budget and the provision of necessary public goods as follows in the mission of Portuguese SOEs: "The activities of public enterprises and the entrepreneurial sector of the State need to be oriented towards contributing to the economic and financial equilibrium of the Public Sector and to the upholding of adequate levels of provision of societal necessities." Dunn (Dunn and Sussman 2008) provides a description of the Portuguese institutional sphere and planning strategy of the transportation sector and contrasts it with that of the US. He writes:

> Although there are some transportation planning efforts in Portugal (e.g., the National Roadway Plan and various municipal transportation plans), transportation strategies tend to emerge from the decisions of nationally-elected leaders in a negotiated setting rather than being planned through a formal process. In this sense, planning in Portugal is a technical activity to support politically-determined strategies, much as it was in the U.S. in the mid-20th century. Constrained by the policies and funding decisions of the central government, transportation organizations develop strategies in reaction to the higher-level decisions of elected leaders. For those organizations, strategy development is largely constrained by the institutional design of Portuguese governance and finance (Nelson 2008).

(Dunn and Sussman 2008)

He concludes about transportation strategies in Portugal:

> In summary, in Portugal, strategies largely emerge, rather than being deliberately planned, from negotiation at the national level, reaction by sub-national organizations dependent on national-level funding and policy guidance, and emergence of strategy at the various sub-national regional

scales. In the US, on the other hand, deliberate strategy is pursued by a variety of organizations as well as at the metropolitan and state scales.

(Dunn and Sussman 2008)

Political influence on technical decision making is very strong in Portugal. On the other hand, transportation enterprises receive public mandates about what they should be doing, but it is important to note that these organizations behave as actors in their own right. Depending on the interests of management and employees of state-owned enterprises, and the incentive and accountability mechanisms in place, the actual strategy and actions of the state-owned enterprises will emerge from those circumstances in addition to the political mandate.

5.2.6 *Funding*

The Portuguese HSR project encompasses several priority links. The envisioned infrastructure cost for the most important rail links is projected at around Euro 4.5B for the Lisbon-Porto axis plus Euro 600M for an HSR crossing of the river Tagus, Euro 1.8B Euro for the Lisbon-Madrid axis, and Euro 1.4B Euro for the Porto-Vigo axis. As is typical for rail projects, operating cash flow is not expected to cover initial construction costs. According to calculations by RAVE, the required state support as percentage of total investment would be around 36%. EU funds would contribute around 19% of the total investment considering both the projected Lisbon-Madrid and Lisbon-Porto HSR Links (**Figure 5-10**).

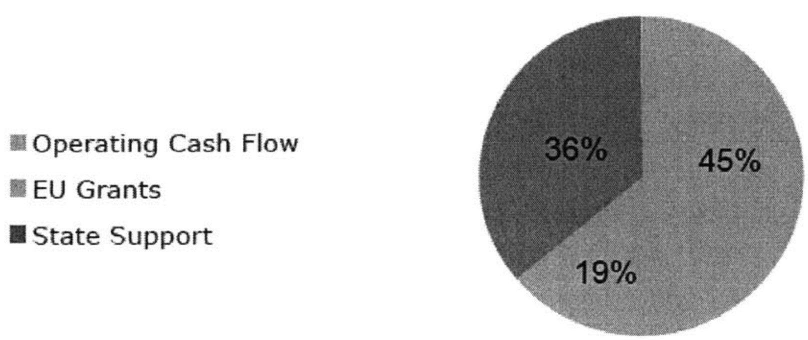


Figure 5-10: *Cost Share Breakdown (2008 RAVE Annual Report, (RAVE 2009))*

5.2.7 *Data for case study*

The case study concentrates on the HSR axis between Lisbon and Madrid, with a possible extension to the seaport of Sines south of Lisbon. Some parameters in the MATE study are assumed as variable despite agreements on their actual design that were made previously, e.g. on the number of stops.

The main data source for the study in this chapter was a collection of 40 reports and technical studies related to the HSR planning effort, dating from the early 90s to the present date, which MIT Doctoral student Travis Dunn from the MIT-Portugal Program had gathered during a visit to Portugal in January of 2009. Additional information was gained through interaction with Prof. Joseph Sussman of the MIT-Portugal Program, MIT Doctoral Student Jorge Oliveira, and visiting student of the MIT-Portugal Program from the University of Coimbra Diana da Silva Leal. Unfortunately, it was not possible to interact with RAVE leadership regarding the set-up of the MATE study. All information presented in the set-up of the MATE analysis is therefore based on assumptions after consulting the listed knowledgeable people and available documents. Any views represented in this chapter are not official positions of the named companies or government bodies. The study is intended to demonstrate the set-up of a MATE study and to enrich the understanding of how MATE can be used as transportation decision making method. The purpose of this case in this thesis is not to provide technical guidance.

5.2.8 Mission statement and identification of stakeholders

The *mission* of the project is hard to define without interviewing actual stakeholders. Several interests play a role for this undertaking, such as prestige, attracting outside funding (from the EU), boosting the Portuguese economy through construction work, and improving travel times for people and freight. For the purpose of this study, the mission is defined as "Improve travel time between Lisbon and Madrid for passengers and cargo, if outside funding can be obtained such that additional debt to Portugal would be kept at an acceptable level." An important question to clarify in interviews is what the maximal level of additional debt for Portugal constitutes. An upper boundary is 3% of total GDP, or $10.6B, in order to adhere to EU stability standards. $10.6B is however the amount of *all* new debt that can currently be accumulated by the Portuguese state in one year.

The project will affect a broad number of stakeholders across the entire nation of Portugal and beyond Portuguese borders. The most important decision-making stakeholders are Portugal, Spain, the EU, and a Private Investor. Portugal, the EU and a Private Investor will contribute to the project funding. *Portugal* (=Portuguese National Government) will be the major recipient among the four stakeholders of the benefits of a stronger infrastructure. The *EU* administers the cohesion funds, which supports projects that foster the integration of European countries through cross-border connections. A Lisbon-Madrid HSR line qualifies for such support, but would be required to have the general European gauge and hence not be compatible with tracks in Iberian gauge in the rest of Portugal. A *Private Investor* would consider the HSR project like any other investment opportunity, expecting a return on investment that would be adequate for the incurred project risk. Since a cross-border connection between Portugal and Spain would invariably touch Spanish soil and require coordination with Spain, *Spain* has a decisive stake in the project.

Portugal, Spain and the EU can only be understood as single actors at a very high level of aggregation. They consist of different negotiating and decision making parties which represent very large population groups.

Other stakeholders with a vested interest in this problem are enumerated below. For the same reason as in the Chicago case study they are assumed to have no decision making power: their interests are only considered insofar as their elected political representatives actually represent them. Important stakeholders are the following:

- Travelers who will use the system (Portuguese, Spanish, international travelers);
- Urban Planners, engineers, and consultants who seek to ensure thoughtful design and integration with other (municipal, national) networks. They will work on this major project for a number of years and need to invest in learning about its unique features;
- Companies which will utilize the freight/shipping services of the HSR network;
- Construction companies and workers who will build the physical infrastructure;
- Future operators of the system;
- Other entities of the Portuguese transportation sector that would need to collaborate with and need to integrate their transportation systems with the HSR system.

These groups of stakeholders are either users of the system whose interests need to be represented by government bodies, or else knowledge producers. Legacy transportation services and the respective organizations (MOPTC, MFAP, SEE, IMTT, REFER, CP) will determine the quality of collaboration with the HSR system and hence influence the quality of the overall surface transportation system in Portugal. For the purpose of this analysis however, the boundaries are drawn around the HSR corridor between Lisbon and Madrid, excluding links to the larger rail transportation system in the country.

MOPTC Ministry of Public Works, Transportation and Communication
MFAP Ministry of Finance and Public Administration
IMTT Institute for Surface Transportation and Mobility
REFER National Railway Network (Standard Rail Maintenance)
SEE Government body managing Portuguese public companies

5.3 Summary of attributes using both MATE and CBA

The list in Table 5-3 summarizes the attributes that the decision-making stakeholders in a MATE study are interested in (with "being interested in" symbolized by an 'x'). The attributes were derived in several brainstorming and review sessions by the author and visiting Portuguese graduate student Diana da Silva Leal of the University of Coimbra, under the guidance of Dr. Adam Ross, after familiarizing themselves with the available material on the HSR project.

Table 5-3: *Attributes and stakeholders for HSR in Portugal*

Stakeholders (right) **Attributes (below)**	**Measure**	**Portugal**	**EU**	**Private Investor**	**Spain**
Total Project Cost (Portuguese side)	€B	x	x		
Cost Portuguese Share	%	x			
Cost EU Share	%	x	x		
Cost Spain Share (Border Connection)	%	x			x
Private Investor Contribution	€M	x		x	
Cost Maintenance	€/yr	x			
Cost Operation	€/yr	x			
Portuguese Cost Share Operations	%	x			
Spanish Cost Share Operations	%				x
Net Travel Time Lisbon-Madrid	min	x			x
# Stops on Portuguese side	#	x			
Overall Travel Time (Pax)	min	x	x		x
Overall Travel Time (Freight)	min	x	x		x
Quality of Coordination at border connection	[1-5]	x	x		x
Max Capacity (Pax)	pax/day	x			
Max Throughput (Freight)	ton/day	x			
Ease of freight transfer to HSR in Evora	[1-5]	x			x
Risk (for private investor)	[1-9]			x	
Security	[1-5]	x			
Prestige	[1-5]	x			

The scales in parentheses for the last four attributes (for example, [1-5]) are ordinal scales to rank qualitative factors that are established by the MATE analyst. They are not official scales as used in any official function. In addition to these attributes, eight key exogenous uncertainties were identified for the MATE analysis that would impact the stakeholder attributes if they were to change over time (Table 5-4). In MATE terminology, these uncertainties are parameterized as "Epoch variables". In a scenario analysis these epoch variables need to be varied so that the impact of their change on stakeholder attributes can be explored. The scales ([1-5]) are again qualitative scales as established by the MATE analyst, as explained above.

Table 5-4: *Epoch variables for HSR in Portugal*

Epoch Variables	**Units**
Demand level	pax/year
Demand level	ton/year
Mode share HSR (pax)	%
Mode share HSR (freight)	%
Economic situation of Portuguese major trading partners	[1-5]
Portuguese Economy	[1-5]
Economic situation of Spain	[1-5]
Threat level	[1-5]

A detailed description of the attributes and epoch variables is provided in the Appendix, along with generic formulas for calculation where available. Intermediate variables are variables that aggregate data and that are required to calculate attributes, but that do not provide value to the stakeholders in their own right. Intermediate variables and constants are included for each attribute as applicable.

5.4 Cost-Benefit Analysis for Lisbon-Madrid corridor

The Portuguese transportation consultancy Transportes Inovação e Sistemas conducted a CBA for the HSR corridors Lisbon-Porto and Lisbon-Madrid, using a methodology proposed by Rus and Nombela (2007). Not knowing the future traffic volume, they calculate the traffic volume that would be needed to offset construction (initial investment), maintenance (annual fixed cost) and operation costs (annual variable cost). A so-called "social discount rate" is employed in the study. The model calculates the difference between total savings to society (travel time savings, savings from not operating conventional rail anymore) and variable maintenance cost of HSR per year. It is then calculated at what traffic volume those discounted net benefits would be higher than initial investment costs, assuming a project life of 50 years. Costs and benefits that were quantified for the analysis are listed in Table 5-5. The study quantifies only first-order effects (those that can be experienced directly by stakeholders of the system). The condition to be satisfied for a positive NPV is the following:

$$\int_0^T [B(Q)-C_q(Q)]e^{-(r-\theta)t}dt - \int_0^T C_t e^{-rt}\,dt > I$$

where
B(Q): annual social benefits of the project,
$C_q(Q)$: annual maintenance and operating cost variable,
C_t: annual fixed maintenance and operating cost,
I: infrastructure construction costs,
T: life of the project,
r: social discount rate,
θ: annual growth of benefits and costs which depends on *Q*.

Table 5-5: *Benefits and costs for HSR in Portugal*

Benefits	**Costs**
Travel time savings	Initial construction costs
Savings from reduced externalities (crash costs, emissions)	Maintenance costs
	Operating costs

Data for the cost modeling of the Lisbon-Madrid corridor were taken from previous RAVE studies. Operation costs are assumed at the level below, which will vary depending on the actual frequency of runs. Average construction costs include a third crossing of the river Tagus.

Average construction cost: Euro 11,733,538.32 per km

Annual (fixed) maintenance cost: Euro 21,053,794.00

Annual operation cost: Euro 44,307,567.00

An average time value of Euro 11.93 per hour is assumed for the Lisbon-Madrid corridor. Rus and Nombela (2007) note that the social profitability of HSR projects depends heavily on the value of time and on travel time savings. Value of time is mostly influenced by a country's level of income. Since Portugal has one of the lowest income levels of the EU countries, it is relatively more difficult to show the viability of a certain investment compared to higher income countries in the EU. Travel time savings are assumed at 70 minutes for the Portuguese part of the tracks.

Only those are quantified in the study. Table 5-6 shows the result of their study. Scenario 1 is tested against a change in discount rates and ignores any reductions in externalities.

Table 5-6: *Required number of passengers in first year to achieve a positive NPV for different discount rates*

	Scenario 1	Scenario 2	Scenario 3
Discount rate	5.5%	4.0%	5.5%
Savings from reduced externalities ($\sum 5$ *years*)	770M	770 M	0 M
Required # passengers	6.8M	5.8M	8.9M

It should be noted that the calculation only refers to the needed passenger number to offset construction costs from the Portuguese side, which are projected in the CBA at 2.4B for the tracks from Lisbon to the Spanish-Portuguese border. In order to generate a positive return to society for the *two* affected countries, the required number of passengers will need to be higher. A number of travelers of 6.8M per year translates to about 18,600 passengers per day. Travel volume as indicated by RAVE (2002) for the corridor Lisbon-Madrid was 1.7M by road, 0.06M by conventional rail and 0.7m by air. Even though the data that RAVE provides is somewhat dated, the sum of 2.46M trips over all modes is significantly smaller than the required numbers of passengers in Table 5-6. The authors of the CBA comment on the required passenger levels:

> Our results show that investment in HSR infrastructure can scarcely ever be justified on the basis of time savings alone and the net willingness to pay of generated traffic. It is some combination of a need for additional rail capacity and the benefits from alleviating road and airport congestion that must form the basis for the case.

(Rus and Nombela 2007)

The following assumptions are explicitly listed in the cited CBA study.

1. Construction, operation and maintenance are conducted by the same organizational entity.
2. No freight is transported.
3. Markets are competitive.
4. Profits of other transport modes remain the same after the market entry of the HSR lines.
5. Conventional rail is used as base case, excluding induced traffic from HSR.

6. Market prices reflect opportunity costs.
7. The cost of using HSR is in the same rough range as the cost of other modes of transportation, so that deviation of traffic to HSR from other modes is a reasonable assumption.
8. Reduced congestion and reduced crash costs are not considered for traffic deviated from road and air.
9. Externalities are ignored (for example emissions, noise).
10. Customers' travel time savings and willingness to pay are the only two benefits that are quantified.
11. Benefits are quantified for the first year and assumed as growing at a constant exponential rate over the life of the project.

It should be noted that the practice of quantifying customers' willingness to pay as a benefit deviates from the CBA practice recommended by the FHA and applied in the previous chapter.

In summary, the CBA does not strengthen the case for the HSR project as therein proposed since the required numbers of passengers are very high. If consensus exists that the likely gap for social viability cannot be bridged from unaccounted for second-order effects (for example, stimulation of economy, prestige), closer attention should be directed to the option of mixing freight and passenger transportation to better use available track capacity and generate additional benefits of the project.

5.5 System concept generation and design variables

This section returns to the set-up of the MATE analysis. After identifying attributes and epoch variables, the factors that the designer can influence are isolated (design variables). Table 5-7 summarizes design variables, including those that will generate different concepts (network routing, mixed freight and passenger operations). The first two design variables, corridor choice and technology choice, distinguish different concepts (indicated by *). Figure 5-1 depicts one corridor choice. Typically the development of alternative corridors requires studies on the local geography in some detail to adjust price estimates and is therefore very work-intensive. The discussion in this chapter assumed that HSR would be built under all circumstances. Taking a step back however, it is also a valid question to ask how intercity transportation could be improved by investing in new connections of the conventional tracks to achieve better travel times. The downside of this option is that for the EU would not fund a project out of the cohesion funds that does not comply with its gauge standards (international gauge).

The design variables were derived in several brainstorming and review sessions by the author and visiting Portuguese graduate student Diana da Silva Leal of the University of Coimbra, under the guidance of Dr. Adam Ross, after familiarizing themselves with the available material on the HSR project and deriving the attributes. DVMs were used on different iterations of design variables to validate that the final selection of design variables indeed strongly drove the attributes.

Table 5-7: *Design variables*

Design Variables	**Units**
Network Routing*	discrete corridor choices
Rail type*	HSR, Conventional
HSR link Sines-Evora	[yes, no]
Cost share Portugal	%
Cost share EU	%
Cost share Private Investor	%
Cost share border port Spain	%
Cost share operations Portugal	%
Investment in good border interactions	[1...5]
Maximum loads conventional	ton/axle
Maximum loads HSR	ton/axle
Train brand	Alston; Bombardier; Siemens
Land port location	2 choices
Border port location	south/north on border
# stops between Lisbon and border	[1...5]

The following DVM (Table 5-8) is the result of the iterative process described above during which the final selection of design variables was derived.

Table 5-8: *DVM Portuguese HSR*

		Total Project Cost (Portuguese side)	Cost Portuguese Share	Cost EU Share	Cost Spain Share (Border Connection)	Private Investor Contribution	Cost Maintenance	Cost Operation	Portuguese Cost Share Operations	Spanish Cost Share Operations	Net Travel Time Lisbon-Madrid	# Stops on Portuguese side	Overall Travel Time (Pax)	Overall Travel Time (Freight)	Quality of Coordination at border connection	Max Capacity (Pax)	Max Throughput (Freight)	Ease of freight transfer to HSR in Evora	Risk (for private investor)	Security	Prestige
Network Routing	discrete corridor choices	9	0	0	0	0	1	3	1	1	9	9	1	1	3	9	9	9	3	9	0
Rail type	HSR, Conv.	9	0	0	0	0	9	9	0	0	9	9	1	0	9	9	9	9	3	9	9
HSR link Sines-Evora	[0-1]	9	9	0	0	9	9	9	0	0	9	9	9	0	0	9	0	9	3	0	0
Cost share Portugal	%	0	9	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost share EU	%	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost share Private Investor	%	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0
Cost share border port Spain	%	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost share operations Portugal	%	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0
Investment in good border interactions	[1...5]	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	1	0	0
Maximum loads conventional	ton/axle	9	0	0	0	0	9	9	0	0	0	0	0	0	0	0	9	0	0	0	0
Maximum loads HSR	ton/axle	9	0	0	0	0	9	9	0	0	0	0	0	0	0	0	9	0	0	0	0
Train brand	Alston; Bombardier; Siemens	1	0	0	0	1	1	3	0	0	0	9	0	1	9	3	3	3	0	0	9
Land port location	[1..2]	9	0	0	0	0	0	9	0	0	9	9	9	0	0	9	0	9	3	0	0
Border port location	south/north on border	9	0	0	9	0	0	0	9	9	0	9	0	0	0	9	0	9	0	0	0
# stops between Lisbon and border	[1...5]	9	9	0	0	9	9	9	0	0	9	9	9	0	0	9	0	9	0	3	0

5.6 Modeling underlying relationships: Next steps

The Portugal case study is more complex than the Chicago case study presented in the previous chapter for the following reasons:

Stakeholders are high aggregates of stakeholder groups. Even though the "City of Chicago" is already a high aggregate of interests, spokespeople and planners from the Mayor's Office can conceivably speak about the City's position on planning issues. The stakeholders EU, Portugal and Spain however are aggregate entities of a different order of magnitude. They represent countries in a parliamentary system that come to decisions through political bargaining and have less direct executive power over their countries than the Mayor of Chicago has over the smaller area of Chicago. Being a supra-national governing body, the EU has less power than national governments and depends even more on alignment of political parties. The answers to key acceptable ranges, such as maximal spending on the project, require deep political insight to be helpful (Is Portugal willing to push the 3% limit? How have recent economic developments impacted the funding ability of the EU and Portugal relative to the available studies?). Going forward in the MATE study, these issues can be dealt with through a) working with assumptions on utility and acceptable ranges, and sensitivity-testing of the tradespace to changes in assumptions about both; b) finding an imperfect proxy representative for the respective aggregate stakeholders to elicit utility information; or c) split stakeholders up into subgroups (e.g., EU representatives on the issue can be split up exhaustively in the decision making bodies European Council of Ministers, European Parliament, European Commission, and Administration of the European Cohesion Funds).

Purely financial stake and limited liability by Private Investor. Unlike in the Chicago case, private capital is contributed from a private investor who lends money and expects interest payments in return. In the Chicago case, the Private Operator assumes temporary co-ownership and managerial decision making power over the Airport Express' operations. In the Portugal case, the Private Investor is a generic money-providing body that has no interests besides assessing project risk correctly, and asks for appropriate market interest payments. Depending on an investor's risk profile, more or less high interest rates are required for a given level of risk. Riskier projects promise a higher return on investment than more secure ones, but at the same time come with a greater probability of loss than more secure investments. Depending on an investor's risk profile the risk-return curve (Figure 5-11) is flatter or steeper. The risk-return curve can be understood as the asking price by a certain investor in order for him to agree to finance a project. The design variables as they were defined in the previous section are at a relatively low technical level that do not map in a transparent way to project risk. A risk model needs to be developed that allows a mapping of different designs to risk as would be perceived by a private investor.

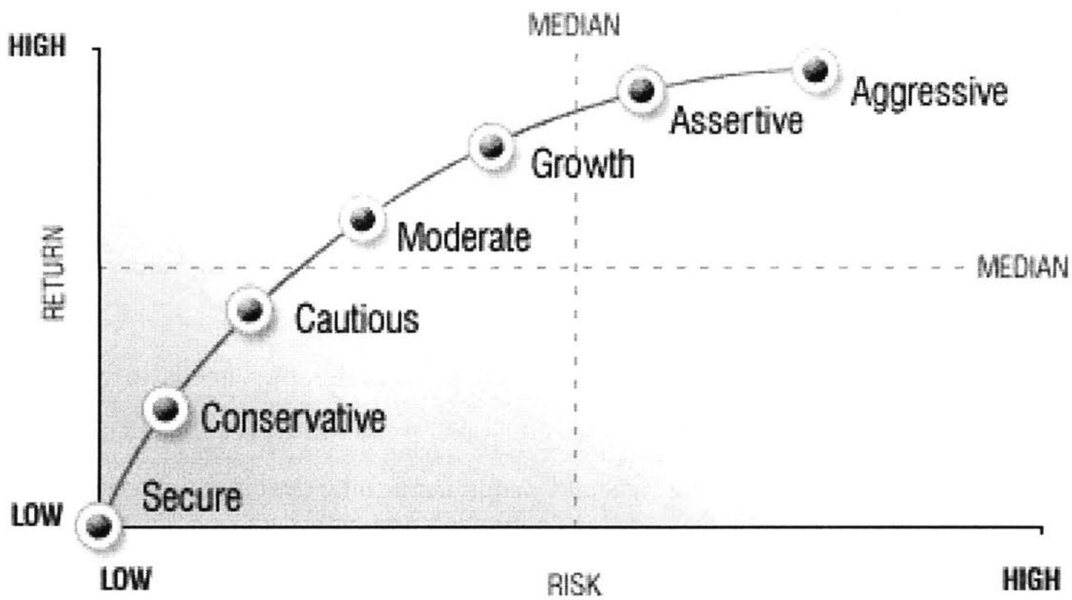


Figure 5-11: *Risk-return curve (MLC 2009)*

Profit modeling. Many expectations are tied to the HSR system, but all of them require that passengers ride the system and logistics companies use it to ship freight. Only with enough business can traffic be alleviated from other modes, harmful effects on the environment reduced, the economy stimulated and hopefully profits gained. The authors recognize for this case study that demand cannot be modeled or predicted accurately for the long time frames involved (useful life span assumed at 50 years). Demand for passengers and freight is therefore assumed to be an external variable to the model. Demand can be calculated from the epoch variables of "overall demand" and "mode choice for HSR" (assessed separately for freight and passenger transportation), both of which can be varied. Based on demand, assumptions for profitability can be made. With information about both ridership and profitability, basic information is available for the assessment of the performance of the HSR system as perceived by its stakeholders. It is possible that the epoch variables for demand (mode choice, demand level) exert a higher influence on "risk" as perceived by the private investor than the technical design parameters in the previous section. The possibility needs to be explored and considered in formulating the risk model.

Capacity modeling. While capacity modeling is straight-forward for single service operations (passengers or freight), the problem becomes more complicated for mixed operations. A scheduling algorithm needs to be employed to output the envelope of capacity and travel times for different percentages of freight and passenger trains. This exercise requires a sophisticated mathematical model, but taps into existing knowledge in Operations Research.

Travel time. Travel time is dependent upon average speed, which is either simple free-flow average travel speed depending on the terrain and track routing, or an artificially lower speed as required by the operations schedule to comply with spacing requirements. A basic technical model for the time loss from decelerating, pausing and accelerating needs to be incorporated additionally to calculate the impact of additional stops on overall travel time. This part requires special knowledge in HSR train operations and would need to be developed in collaboration with a domain expert.

Network routing. Only one possible network has been referred to in this chapter (Figure 5-1). Additional networks may however be developed that represent additional concepts. While average values exist for the construction cost per km of track, bridges and tunnels can add substantial cost and need to be considered on an individual basis. To develop and cost additional options collaboration with a domain expert is required.

5.7 **Discussion**

5.7.1 Importance of local context for case study

A look at the institutional context reveals a situation that resembles the policy-driven, cost-centric planning process of the 1960's in the US. Central planning has a strong tradition in Portugal. Policy makers decide upon a desirable project from their point of view, which engineers then have to implement at lowest cost. The strong focus on cost, however, makes it difficult to keep the value of the project in mind, the mission that it is ultimately intended to fulfil. At the same time, politicians may not have a comprehensive technical understanding of the properties of different options (such as strong investments in the existing track infrastructure).

The transportation sector in Portugal is owned in large part by the government and controlled in the form of state-owned enterprises. The merits and dangers of state-owned enterprises have been discussed in section 5.2.5 in this chapter. State-owned enterprises protect societal interests from the pressure to be profitable or disappear, but at the same time lack market incentives for efficiency that pressure for profitability brings about. When SOEs exist in the chain of command from policy makers to executing engineers (who may work under contract or be employees at the SOE), a smooth passing on of directives should not be assumed. As discussed in Chapter 2, organizational processes and interests may introduce "noise" to the mission "signal", which should be considered in the mission and attribute elicitation process.

5.7.2 Comparison of insights from MATE and CBA

From the set-up of the MATE analysis and the referenced CBA, information is gained about the insights that both methods would provide if they were conducted in complete form at the beginning of project planning. Both methods try to answer different questions and therefore provide complementary insights into "blind spot" areas of each other. MATE seeks to ensure that stakeholders' expectations are met for what a project should deliver, whereas CBA ensures that dispersed interests of society are taken into account. The question of how intangible and non-monetary costs and benefits can be included in a project evaluation, and how MATE and CBA can be used together in decision making, is further discussed in Chapter 6.

1. Cost-focus of attributes

A large number of MATE attributes refer to the split of costs between different stakeholders, suggesting that cost shares are a major concern for the project. The assumption in CBA that construction, operation and maintenance costs are paid for by a single entity veils important dynamics of interests between different decision-making stakeholders. In reality, different actors pay for and execute those functions. It is important to be aware of the effects that are created by the fact that government subsidies (EU, Portugal) are typically only granted for initial construction costs, but not for operating costs. In addition, different cost types can, to some degree, be directly traded off (higher initial investment for lower ongoing maintenance cost, and vice versa), which has to be considered in addition to the nominal cost shares that different actors pay in the beginning. The question of who should pay for what and how much overshadows the question of what a "good" system design would be to accomplish a specific set of goals (cost-centricity vs. mission-centricity), which may be a problem in ensuring value delivery to non-paying users.

2. Intangible costs and benefits

Intangible benefits exist that do not occur to society as a whole, but that are valuable to individual stakeholders, for example prestige gains for Portugal. Like managerial control in the

Chicago case, these intangible attributes do not always need to come at monetary cost, or in expenses that could be expressed in monetary terms. Stakeholders however may care strongly about them. It is questionable if and to what extent these details would have been revealed in a traditional project evaluation process, such as CBA.

Rus and Nombela (2007) comment in the following way on the assessment of the economic rationality that they seek to assess in their CBA:

> The case for High Speed Rail (HSR) infrastructure depends on the capacity of generating social benefits which involves the construction, maintenance and operation. Decisions to invest in this technology have not always been based on sound economic analysis. A mix of arguments, besides time savings –strategic considerations, environmental effects, regional development and so forth– usually makes the discussion on the economic rationality of investing in HSR vague and imprecise.

(Rus and Nombela 2007)

Whether or not one agrees on the implicit priority given to economic rationality in the referenced statement, the observation of the existence of multiple tangible and intangible benefit and cost types is supported. These costs and benefits, monetary or non-monetary, are important to stakeholders in the decision making process and should therefore be incorporated in the planning process. Practical problems with interviewing high-level decision makers and eliciting potentially sensitive information have been discussed in Chapter 3. Decision theory maintains that an individual has the highest authority about his preferences. Preferences cannot be right or wrong, they are subjective and individually different. A politician with a public mandate however is in a different position since he represents his constituency and needs to be able to justify prioritized attributes. Hard-to-argue-with criteria such as economic rationality are therefore attractive for justifying decisions, even if the underlying idea is NOT profit maximization (which can be assumed for virtually all cases of public transportation).

3. Consideration for dispersed benefits and costs to society

Neither MATE nor CBA can be relied upon to bring up all important considerations that need to be weighed in a decision. CBA assumes a broad view over all affected stakeholders, whether they have decision making power or not. As in the Chicago case and in many transportation projects in general, travel time savings are a (often *the*) major driver of project benefits. A CBA specifically quantifies this element which consists of many small benefits that occur to a large number of people, whether decision makers prioritize them as a decision metric or not. If decision makers do not prioritize this attribute for the MATE analysis, a substantial benefit of the project would be overlooked.

Chapter 6 Discussion

This chapter reviews the research questions, summarizes research contributions, and discusses areas for future research.

6.1 What design methods are used for transportation systems planning? What are their limitations? What alternative system analysis methods are available?

6.1.1 Analytic tools

Different analytic tools exist that help rank available alternatives. Tools typically used in transportation planning are Cost-Benefit Analysis (CBA), Financial Analysis, Economic Impact Analysis and Environmental Impact Analysis. CBA is a particularly established method next to financial analysis for answering the question of whether to proceed with a project or not. Both CBA and financial analysis are the first analyses to be performed in the early evaluation stages of a transportation project. Financial analysis seeks to answer the question whether a project will generate a financial profit. While this information is important for planning, it is not a well-suited decision criterion in the reality in which transportation systems are constructed and operated. Transportation fulfills important societal functions, such as enabling mobility to underprivileged areas, for which important reasons exist why they should be subsidized if the government deems its service sufficiently important for the government's constituents. Sufficient importance can, for example, be established if the enterprise provides significant non-monetary benefits to the population or the environment, such as enabling trips to work, linking businesses through the provision of transportation infrastructure, or by reducing external costs to the environment. It is for this reason that a financial analysis is informative for transportation planning, but cannot be relied upon to assess whether a project is a good one, nor whether it should proceed (even though financial self-reliance makes the case for a project a lot easier).

The second key decision-making method for transportation planning next to financial analysis, is Cost-Benefit Analysis (CBA), which tries to elicit non-monetary benefits of a transportation project to answer the question of whether a project will provide a net benefit to society. For this reason, CBA as an established transportation decision-making method is used as a reference point against which to compare the insights that are gained through the evaluation using MATE. Even though CBA is established, tested, discussed, and codified in several countries, it exhibits a number of methodological and practical shortcomings, which are discussed in Chapter 2.

6.1.2 Decision making models

Analytic tools are only part of evaluating the goodness of different design options. Taking a step back, different models exist for how transportation decisions are made (with varying prescriptive strength), in which analytic models can be embedded.

The rational planning model has been used historically as the model for decision making in transportation planning. Assumptions that underlie this model include:

1. The "goal" that should be defined in the first step is assumed to be unambiguous and clearly definable.
2. The decision maker is assumed to act exclusively in the capacity of rational technician, ignoring other roles such as "advisor, mediator or administrator"
3. Enough resources (money, time) are available to evaluate all generated alternatives according to the established evaluative criteria.
4. Stable preferences are maintained over time.

Rational planning, the decision making model that underlies MATE, is the process of establishing evaluation criteria for a specified problem, generating a set of alternatives, and subsequently evaluating alternatives. Other decision making models have been suggested that eliminate certain underlying assumptions, but bring their own assumptions to the table. Relaxing assumptions ceteris paribus makes a method better, but relaxing an assumption at the cost of introducing a new assumption is not easy to evaluate. The decision making models discussed in Chapter 2 in addition to rational planning are the following:

1) *Satisficing* assumes several resource constraints and the fact that it is not possible to generate all relevant solutions to a problem and compare them. The advantage is a pragmatic approach that seeks to factor into the decision the cost for information gathering and processing by accepting the first solution to meet a specific set of criteria. A negative consequence is that by "settling," superior designs (potentially by a wide margin) are ruled out.

2) *Incremental change* eliminates the assumption that a desirable goal can be formulated for a transportation decision problem (for example, because it is too politically controversial). While this is a strong relaxation of a fundamental assumption for planning in general, this model assumes a very constrained solution space in which only a limited number of alternatives can be identified, and the consequences of those alternatives can only be evaluated to a limited degree. In addition, multiple decision makers are not in a position to coordinate effectively. A danger in adopting this decision making model is a too constrained view on the design space, which may rule out superior designs out of an ex ante too pessimistic assessment of the ability to implement more "bold" options.

3) *Organizational process* stresses the idea that all decisions are the outputs of organizational and institutional structures, channels of communication, and Standard Operating Procedures. The assumption that the decision maker acts exclusively in the role of rational technician is relaxed by the recognition of how institutions, organizations and social norms shape decision-making. While the decision-making process is goal-oriented, the actual goals that an organization eventually pursues emerge from goals that relate to the problem at hand as well as individual, group, and organizational goals of the involved individuals. Organizational process as a decision making model explicitly recognizes the irrational in that it seeks to achieve goals other than the primary objective, allowing for the influence of social and cultural processes on a decision outcome. A disadvantage of the explicit recognition of the influence of organizational processes in decision making is that it might deemphasize the rational aspect of planning and the power of the designer to change things into a more desirable direction.

4) *Political bargaining* recognizes that in a situation in which different decision-makers with conflicting interests and channels of influence exist, and a single decision-maker assumes multiple roles, the outcome of any decision-making process is the product of bargaining, rather than a purely rational or optimized solution. Political bargaining explicitly recognizes the importance on a decision outcome of politicians' personal interests and changes in political goodwill. Those factors again may be labeled irrational, if irrationality means that factors that do not pertain to the immediate problem play a role

in a decision. A disadvantage of the explicit recognition of the influence of political bargaining in decision making is that it might deemphasize the rational aspect of planning and the power of the designer to change things into a more desirable direction.

MATE is an emerging method in systems engineering, based on the rational planning model, but (in Dynamic MATE) eliminating the assumption that preferences have to be stable over time as well as the existence of clearly defined, unambiguous goals, by allowing for ranges of attributes instead of sharp requirements, and the ability to consider latent value. In addition, MATE eliminates assumptions about the behavior and preferences of stakeholders by employing a value-based approach: decision-makers are interviewed and their preferences are used as decision metrics. Different roles of the decision-makers, if they exist, are traded-off during the utility elicitation process and reflected in the expressed attributes and utilities. MATE supports the generation of solutions and maintains that all relevant solutions for a problem can be assessed, at least at a low-fidelity level. In this regard, it is more open to potentially superior solutions than Satisficing or Incremental Change, since those two methods maintain that it is impossible to assess all relevant alternatives during conceptual design.

The underlying idea of MATE is that decision makers should be satisfied with a system that fulfils their expectations. In situations in which decisions about the welfare of stakeholders need to be made, who cannot advocate for themselves when the decision is made (public, future generations, environment), the question about the desirability of guiding principles for a representative decision maker comes up. The legitimized decision maker needs to trade-off both personal, organizational and constituency interests (in his best value judgment) when formulating what outcome would make him or her satisfied with a solution. In order to ensure consideration for the represented constituency and to help guide considerations when making decisions, guiding principles can be established for representative decision makers (such as in CBA). In the MATE application to the case study on the Chicago Airport Express, the stakeholder-elicited attributes varied considerably from the prescriptive CBA attributes. This observation can be due to the fact that decision makers indeed do not care (strongly) about, for example, CBA attributes (public good, environmental preservation), or that there was an implicit assumption that someone will make sure that whatever guiding principles exist will be enforced (and a stakeholder can therefore prioritize personal and organizational objectives stronger). Examples for such personal and organizational objectives for the City of Chicago (which has the clearest public mandate) are tax revenue and generation of employment.)

Future research will need to address how a value-based approach of decision making should be used with stakeholders, who are tasked with representing multiple interests (including interests that might not coincide with their own). In the extended understanding of engineering systems, value (traditionally: requirements) capture is an important task of engineers. MATE recognizes that in order to satisfy a customer, the design engineer must support him in formulating what he really wants (as a starting point before discussions about compromises). In engineering domains in which environmental resources and people's lives are touched, such as the infrastructure domains including transportation, engineering decision making is linked to decisions about the distribution of welfare. A decision maker who is tasked with responsibility for multiple constituencies and causes, as well as his own well-being (e.g. in terms of advancing his career, avoiding controversy etc.), is in a difficult position to openly explore "best" outcomes to an engineering system problem. An important area for research in engineering systems is how a design engineer can support a decision maker in explicitly stating conflicting interests and exploring design solutions. It is not the task of the engineer to take over the task from a legitimized representative for making decisions and value judgments. Recognizing that controversial decisions and value judgments are inherently part of (some) technical decisions however, the question of how to support a decision maker in expressing those attributes (even if difficult and controversial) and understanding different designs' impact on them, becomes part of the design engineer's job.

In the US, transportation planning has largely been shifted over to the responsibility of engineers. Knowledge of technical possibilities and the impact of design options on different attributes is important knowledge to have when making political decisions that have a technical implementation. It appears that in the two cases that the author studied for this thesis, only very limited exploration of technical options with joint discussion with policy makers about different impacts (that need to be assessed technically, such as emissions etc) is taking place. MATE is an approach that supports the goal of more interaction between decision makers and engineers in design development and exploration. An important area for future research is the question of how the elicitation of a broader range of attributes (political, organizational, and strategic, such as economic development) can be supported by the design engineer. Underlying this suggestion is the authors' belief that even in the presence of controversial and messy objectives, the explicit recognition of those objectives places the decision makers and supporting analysts in a better position to make a satisfactory decision. This statement leaves open an immense range of questions of how those different attributes should be treated in an analysis and how they can and should be evaluated.

6.2 What implementation issues arise if MATE as a design method from the space domain is applied to the transportation domain?

A "*mission objective,*" as required as the starting point for a MATE application, has not emerged as a well-defined, integral concept of project planning for transportation in the same way it does in the military, space, and business communities. Instead, the mission to meet demand is often implied and a number of competing goals are enumerated with a pledge to more or less reconcile them. Possible reasons for this difference are discussed in Chapter 3.

Transportation, especially public transportation, has a *complex stakeholder structure*. Individual decision makers need to trade off multiple interests in their heads when expressing their own interests. Large numbers of individuals bear the value and harm delivered by transportation systems, and therefore have a stake in its design. Large numbers of stakeholders require aggregation and representation of interests. The decision making models discussed in the transportation domain and the importance of building coalitions and converting enemies shows the critical importance of stakeholder alignment as a prerequisite for the execution of any plans. The assumption of one or two single decision makers, or a supra-decision maker who individually aggregates and represents interests, are for the most part not reasonable assumptions for transportation design problems.

Transportation engineering touches problems of *equity* and requires value judgments. The task of the engineer cannot be reduced to a purely technical exercise, but neither can politicians ignore the required value judgments inherent in engineering decisions and pass it on as the sole responsibility of engineers.

Inheritance brings with it the need to evaluate a new system relative to a status quo of performance. Optimal use of the status quo infrastructure with minimal improvements (base case) always represents an important architecture alternative that needs to be evaluated along with any new concepts. Inheritance brings with it the stickiness of the status quo and the attachment of people to things they possess. Inevitably, people's expectations are shaped by previous experiences (soft inheritance). Prospect Theory helps explain the stickiness of the status quo. Even though utility theory may lead to better decision outcomes in the long run, people's immediate frustration if something is taken away from them (especially when someone else made the decision) is real and needs to be dealt with.

Several cost types exist for transportation in addition to monetary costs. Even monetary costs are not all the same "color of money" (initial cost, recurring cost) and important reasons exist for why they might need to be treated separately and therefore not aggregated. Costs come in the form of harmful effects to human life and the environment, as well as in the form of necessary spending of scarce resources (time, money).

6.3 What methodological insights emerge through the application of Cost-Benefit Analysis and MATE, individually and complementarily?

MATE and CBA are complementary methods that provide different insights into design problems. CBA assumes a broad view over all affected stakeholders, whether they have decision making power or not, and seeks to ensure that net benefits to society outweigh net costs. MATE seeks to best meet decision makers' expectations for a system. Rus and Nombela (2006) note that the social profitability of High-Speed Rail projects depends heavily on the value of time and on travel time savings. The importance is exemplified in the CBA in the Chicago and Portugal case studies. Benefits from travel time savings are small but occur to a large number of people. While CBA specifically quantifies dispersed benefits to society such as travel time savings, this substantial benefit would be overlooked in MATE if decision makers do not to prioritize it (and in fact it was not a high-priority attribute in the Chicago case study).

Intangible benefits exist that do not occur to society as a whole, but which are valuable to individual stakeholders, for example prestige gains for Portugal. Like managerial control in the Chicago case, intangible attributes do not always need to come at monetary cost, or at expenses that could be expressed in monetary terms. Stakeholders however may care strongly about them. While those attributes are not captured in CBA, the value-based approach in MATE makes it possible to consider all attributes that stakeholders care about. Risks that CBA always carries include potential biases that are introduced through the quantification and discounting of intangible benefits and costs. MATE offers the ability to separate out attributes and keep them separate during the evaluation process, thereby mitigating the risk of skewing the analysis through, for example, the aggregation of more or less certain projections for different attributes, and problems with quantification (e.g., impact of low wage levels in Portugal compared to other European countries).

Based on the analysis in Chapter 4 using CBA and MATE, BRT is recommended for further study. This concept was not even considered in the original technical studies because of prestige concerns. The built-in solution generating part of MATE ensured in this case that a promising and potentially superior solution was considered, which had been ruled out in original studies. The solution-generating tradespace exploration appears to be a useful tool for use in the transportation domain. The fact that a technically promising architecture concept, BRT, was purposefully excluded from original studies points to important concerns of political feasibility. If BRT appears to be the dominant solution in analyses, but something prevents decision-makers from investing in the most basic preliminary studies, factors may be at work impeding the implementation of a design solution even if it appears to be theoretically Pareto-optimal. In the case of BRT, these factors appear to be prestige and the political will to dedicate one of the five lanes of the Kennedy Expressway to public transportation. Important research questions for future work are tied to this general observation: If we know Pareto-optimal designs, will stakeholders actually choose one of them? If not, what factors impede their choice and how can they be overcome?

In the case of BRT, suggestions are made in Chapter 4 for how opposition could be countered. Underused capacity on the BRT lane may be leveraged by offering it up to commuters against payment of a toll. Laid-off CTA employees could be compensated adequately for the loss of their jobs, retrained, or a combination of both. The related research question is: "What attributes are missing from the analysis to prompt a search for solutions to political opposition in a more structured way, rather than leaving it to the knowledge of the analyst?"

6.4 What insights are gained from the application of MATE to two transportation case studies for both MATE and transportation planning?

6.4.1 Lessons learned from transportation cases for MATE

1) From the Chicago and Portugal case studies, literature review, and comments by practitioners, it appears that narrowing the stakeholder structure to a relatively simple one (1, 2, or one aggregate stakeholder) is very difficult. Even a narrowing to only 3 or 4 designing and decision making stakeholders as done for both case studies needs to rely on the interviewed stakeholders' ability to appropriately represent in their decisions stakeholders with only veto-power or no decision making power at all. The elicitation of accurate attributes is a crucial prerequisite for leveraging the advanced analytical tools that have been developed with and around MATE (especially Dynamic MATE) for applications in the transportation domain, and other domains with similarly complex stakeholder structures. Accurate means, in this context, representing the true intensity with which a stakeholder is interested in intrinsically motivated attributes (that the stakeholder personally receives value from) and in attributes that he is interested in on behalf of his constituency. This question may be a very difficult one to answer for a decision maker, since it calls for explicitly making tradeoffs that a stakeholder might rather keep unarticulated.

2) Framing issues can arise when MAUT is applied to stakeholders in a transportation multi-stakeholder problem space. The author perceived, during the interviews performed for the Chicago case, that stakeholders behave differently when they believe that they have to express attributes as a single decision maker, vs. if they know that other stakeholders exist that will advocate for certain interest groups. In the interviews for the Chicago Airport Express, the interviewees inquired which other stakeholders were also to be interviewed. The reason for the interest in other interviewed stakeholders may be a common understanding that below a basic level of satisfaction, even non-decision making stakeholder groups have the power to delay the project and increase project costs (law suits, petitions). Knowing which other stakeholders will be interviewed may give them an idea of what other interests are already represented in the study, and therefore do not have to be incorporated into their own preferences. MAUT was developed with a single decision maker in mind. For multiple decision makers, individual MAU-models can be elicited and thereafter combined, or a single

MAU-model can be elicited with multiple stakeholders present in a joint setting (for example, MCDA). MAUT by itself is, however, not a method developed to aid in stakeholder alignment. Since the Private Operator learned that the CTA and the City of Chicago also expressed attributes, he could assume that the concerns of the public would be represented and could therefore concentrate on his more specific interests. The Private Operator interests concerned only profit generation and advantages in possible contracts with the City of Chicago and the CTA, which those stakeholders did not consider in their attributes (but might very well be interested in when presented with the Private Operator attributes, so as not to be taken advantage of). From the author's internship experience at the CTA, it appears that the CTA is very aware and mindful of their mission as a service provider to the entire Chicago public. The airport express has raised controversy beforehand because of equity concerns and the (rather wealthy) demographics who would benefit from the project. However, since informed that the City was also interviewed (because the CTA interviewee introduced the author to the other two interview partners), the CTA did not include the attribute public acceptance or fare level, even though the interviewed planner is personally very aware of discussions about equity impacts of the project. Asymmetric information on the side of the CTA is a methodological failure in setting up the interview, since decision makers need to express all of his attributes independent of what others might have already said, so that their interests can be understood with minimal bias from asymmetric information. When eliciting attributes from transportation stakeholders, information about what other stakeholders are interviewed (and what interests are therefore likely to be advocated) frame the values these stakeholders express.

3) The Chicago case study reinforced the importance of *evaluability* of attributes for any decision making process. MATE and all other cited decision methods presume that decision criteria are evaluable. In MATE, attributes are the decision criteria used for assessing the goodness of each alternative being evaluated. When conducting the stakeholder interviews for the Chicago case, the question of what stakeholders expect to get out of the airport express (clarified by what they expect the airport express to deliver/ what would make them view the airport express as a successful system) was pushed back to varying degrees by all three interview partners. They were skeptical as to how attributes such as employment

generation, ROI, or increased tax revenues would be of any help in designing the airport express. The difficulty in evaluating those criteria became clear upon later questioning (after the interviews) about how these attributes could be used to distinguish between any two designs options A and B. At the (architecture) concept level, e.g. bus vs. train, a differentiation based on a rough estimation may be possible. For detailed technical planning however, these attributes are not useful. In order to make the high-level attributes operational for the case study, they had to be broken down into attributes that the designer could actually influence. Part of the definition of an attribute is that a decision maker needs to be able to use it to decide between any two design options. The author only asked for what kind of quantitative metric a decision maker would look at to evaluate a specific attribute, and later went on to research which models would produce the metric. The existence of a quantitative metric that COULD be used to differentiate between any two options is however not useful if no data and no models are available to practically use a model to differentiate between any two solutions. For future MATE studies, it is important to follow up in the interviews with questions about where decision makers would get data from to base an assessment of the attribute on, and which models they would use. High-level attributes that are only suitable to distinguish between architecture concepts, if at all, would have been dismissed at that point. From the point of view of understanding the decision makers' real considerations regarding the Chicago Airport Express (even if not evaluable), the interviews were, however, very insightful. The choice of attributes expressed by the City may also be a consequence of the fact that the decision for a design or architecture concept for the Airport Express is closely linked to periodic portfolio decisions about which projects should be implemented at all.

4) The CBA and MATE attributes and decision criteria differed considerably. This fact can be due to several reasons: 1) Decision makers did not consider CBA attributes as important during the interview, or chose not to prioritize them, or did not think of them at all, 2) CBA excludes attributes that are not evaluable, 3) CBA is the result of deliberation about what attributes are of public interest, and agency-specific attributes (such as cost share or managerial control) are excluded from the codified method.

6.4.2 *Insights from MATE for transportation planning*

1. Both political vision and technical knowledge are important when choosing transportation designs. In the 50s, the planning process in the US was a political process in which policy decisions (on highway design) were passed on to engineers who had to implement them at lowest cost. In the US today, the task of making the political decision of what should be done at all is largely in the hands of transportation planners and only subject to approval by policy makers. In Portugal, the planning process still resembles the largely political process in the US in the 50s. These two situations show different reactions to the question of how to combine political values and technical expertise into the decision making process. A real feedback cycle between goal capture and low-fidelity technical modeling and evaluation of different design options, as suggested in MATE, however does not seem to exist, which would improve communication about system expectations and technical options. Research on how to improve decision making in the transportation domain in the US or elsewhere should consider the benefits of a stronger dialogue between designers and policy makers. The iterative process of eliciting attributes and confronting decision makers with the results is a sophisticated tool to facilitate communication during this process.

2. From the literature review, classes, interviews and talks by transportation practitioners during two years in graduate school, the author has not come across any description of how a creative solution-generating process for transportation problems would be analytically supported. In transportation decision making frameworks the step "Generate solutions" typically goes without further explanation. Tradespace exploration is a tool from the space and defense domain that offers structured analytical support for solution generation and evaluation. Aside from scoping the problem and eliciting evaluable attributes appropriate for that scope, the application of MATE to the transportation domain is relatively straight-forward (that is, once the question is articulated of how a specific mission can technically be fulfilled). In the case studies, the question of appropriate system scope (and decision analysis method) was made more difficult since, in both cases, no clear differentiation between the portfolio decision for whether a project should be pursued (along with a programmed budget and time plan) and the conceptual design for a decided upon project was made and tended to be mixed. In order to use MATE for transportation applications, the process of capturing

attributes as decision metrics needs further research into what an appropriate scope of the analysis would be (portfolio decision, conceptual design, mixed levels of analysis?).

6.5 Future work

BRT turned out to be a superior design option in the Chicago case study, yet the unarticulated attributes of "prestige" and "low work force turnover" prevented this option from being included in past official design studies. The fact that public perception can be influenced by marketing campaigns and presentation of facts by politicians shows that these factors are indeed attributes, and not hard constraints. The influence on public perception by the design variables "marketing" and "political speech" may however not be fully understood, even though marketing and public policy have developed tools to predict the impact of public campaigns on buying behavior and public perception, respectively. The question of whether a political environment in which transportation decisions are made can be completely modeled in terms of unarticulated attributes also needs to be addressed. This question is linked to those that were raised earlier in this chapter: If we know Pareto-optimal designs, will stakeholders actually choose one of them? If not, what factors impede the choice and how can they be overcome?

Meyer and Miller (2001) describe the transportation planning process as an incremental one, subject to unfortunate external constraints (only a limited number of alternatives can be identified, the consequences of those alternatives can only be evaluated to a limited degree, multiple decision makers are not in a position to coordinate effectively). The question of whether the transportation planning process can and should be moved (and if so, how?), towards a more rational one needs to be addressed. An essential question to answer in the context of planning is what rationality means. Attention should also be paid to the different levels of decision making, of which the two of portfolio decision making and architectural decision making were mentioned in this thesis. An open question is whether the keeping separate of different decision levels would be desirable from a rationality standpoint, or alternatively, how decision making methods could be applied across those levels of analysis if they can not be realistically separated in a given situation (such as commitment to a transportation project, but repeated deferral because of higher priority projects arising).

Attributes that stakeholders are interested in include those that pertain to the design problem at hand, and others, such as personal and organizational objectives. Both classes of objectives are important to decision makers and drive their behavior. An important question is how and to what extent "irrational" or "non-technical" attributes should be included in technical design. One approach is to include them as MATE attributes and treat them the same as more performance-related attributes. A second possibility is to make a distinction between technical and non-technical evaluation (political goodwill, public acceptance, political realizability in general). The following section suggests thoughts on this question that might be incorporated into future research. A "policy analysis module" could combine methods that are used in the social sciences for the practical evaluation of different" non-technical" factors (for lack of a comprehensive, positive term). An assessment as a result of the policy analysis module, possibly in form of a score for political complexity, could be added as an additional dimension to each design or design group. When the MATE process is reiterated, decision makers are confronted with the results from the policy analysis and can jointly think about if and how political realizability could be increased (e.g., marketing campaigns). This process would lead to the inclusion of new design variables. Even if no counter-measures exist to reduce certain political complications, new knowledge is gained by decision makers about the cost in terms of value loss between the technically Pareto-optimal design and a second design that is easier to implement politically. The idea of the policy analysis module is to recognize the importance of "irrational" considerations in engineering design, and to keep two different evaluation dimensions separate, at least until future research has established that they can and should be fused into the same evaluation method. The addition of a separate policy analysis module within the MATE process could contain elements of MATE, such as attribute elicitation of "irrational" objectives (Figure 6-1).

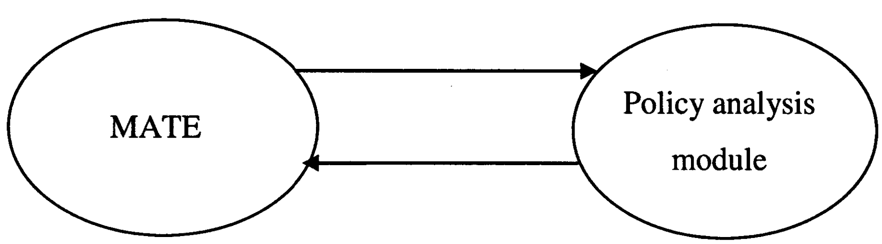


Figure 6-1: *Suggested policy analysis module complementing the MATE process*

A major question for the domain of Engineering Systems is the one of "what characteristics do engineering systems share across domains?", and "how can this knowledge be made useful in developing and applying methods across disciplines?" This thesis characterized the cross-domain application of MATE to a transportation problem, revealing several domain-specific characteristics pertaining to, for example, the understanding of problem scope clarity, time line of decision making, and the relationship to broad stakeholder groups and the existing natural and legacy environment. It will be very interesting to see MATE applied to other engineering systems domains beyond space and transportation, in order to draw further conclusions about engineering systems principles.

Chapter 7 Appendices

7.1 Appendix: Multi-Criterion Decision Analysis

The New Approach to Appraisal (NATA), which is a framework used to appraise transport projects and proposals in the United Kingdom, is a major practical application of a Multi-Criteria Decision Analysis (MCDA)-based approach to support Government decision making. Other applications of MCDA approaches used by the UK Government are set out in its own MCDA manual. MCDA is a formal discipline aimed at supporting decision makers who are faced with making numerous and conflicting evaluations. It is a method for project appraisal aimed at highlighting conflicting or competing goals and helping to resolve these in a transparent way.

Multi-Criteria Decision Analysis (MCDA) and decision conferencing

Like MATE, MCDA is a value-based decision analysis method based on Multi-Attribute Utility Theory (Keeney and Raiffa 1993). MCDA has been advanced especially by researchers at the London School of Economics and has been applied in practice for public and private sector decision making in different contexts, such as transportation, nuclear waste management, research portfolio selection, and others (Phillips and Bana e Costa 2007); (Phillips, Morton et al. 2008). The application of MCDA in the public domain has been codified in the UK, and the funding of its application to practice projects has fostered research in this area by different universities in the UK. MCDA is both a class of decision-analysis methods and a specific individual method. The individual method is described for example in (Phillips and Bana e Costa 2007).

The goal of MCDA is to highlight conflicting objectives and to come to a decision in a transparent process. Five problems are attempted to be resolved by its developers: allocate resources in the presence of multiple conflicting objectives, make decisions in the presence of a large number of options without exploring all of them in detail, collectively allocate resources to different business units for collectively optimal decisions, and take into account the human process of decision-making involving formally and informally influential people (e.g., superiors, informal experts). To advance the latter goal that deals with facilitating negotiations, the cited authors have explored the use of *decision-conferencing* as a tool for pooling knowledge of different people and embarking on a joint process of finding a solution. Involving all decision makers in the process of collecting knowledge and developing a joint solution increases the odds of different actors buying into the solution. The term "solution" here

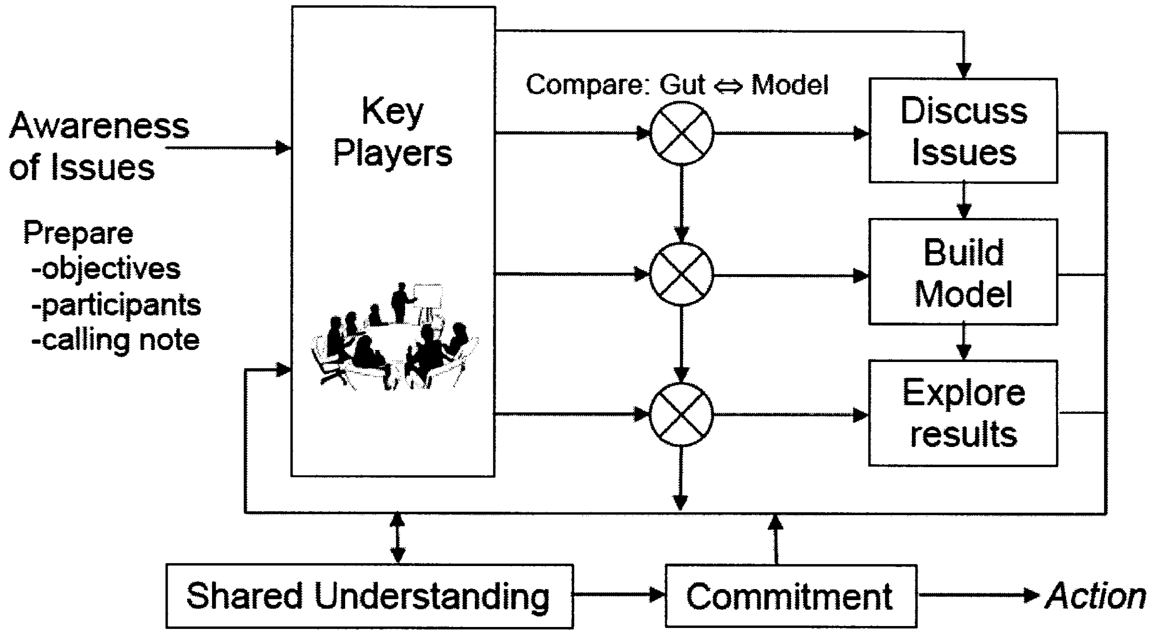


Figure 7-1: *Schematic from a decision conferencing process (Phillips 2006)*

refers to the solution of a decision problem, such as candidate selection, resource allocation or portfolio compositions. According to the authors of the cited papers, encouraging experiences were made with decision conferencing (Phillips and Bana e Costa 2007; Phillips, Morton et al. 2008). Phillips (2006) describes the process of a decision conference, which is summarized in Figure 2.

Decision conferencing is a way of helping a group of stakeholders resolve important issues in their organization by working together, using the aid of a decision analysis model that captures participants' perspective on the issues. The effort is guided by an impartial facilitator and is developed on the spot over the period of about two days. The group jointly discusses issues, develops a group mission, attributes and utilities, and explores options and results of the utility model. Participants are encouraged to express dissonances between model results and their personal intuitive judgments at any time to stimulate the discussion and help refine the model. Throughout the course of the decision conferencing process participants are not only guided to reach a decision during a limited period of time, but practice has also shown that they develop a sense of alignment and shared commitment (Phillips 2006). MCDA and decision conferencing have been frequently applied together as a blend of technical analysis of different objectives and perspectives involved, and a social process to involve the concerned human beings. MCDA calculates the NPV for different solutions. In a business environment this would be the result of a

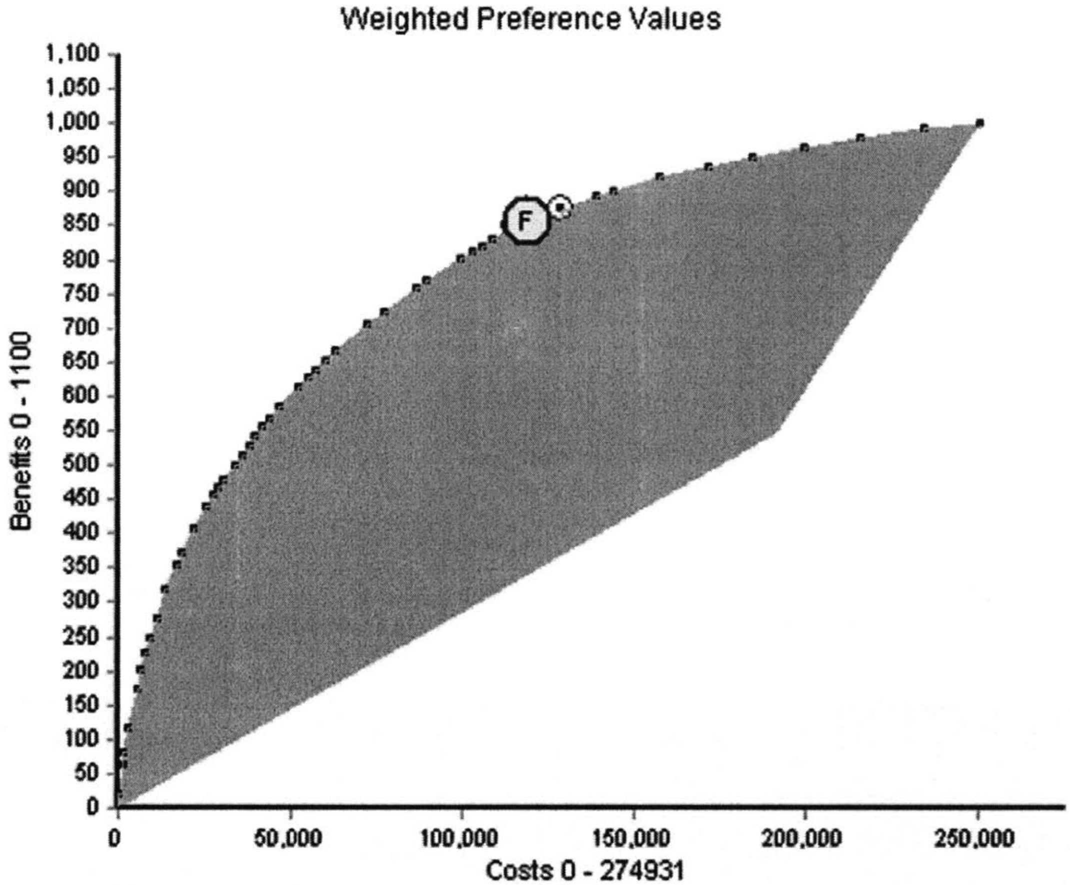


Figure 7-2: *An efficient frontier created from an MCDA model.*

The graph displays cumulative benefits versus cumulative costs. Each point represents another project, with the F position defining the affordable portfolio all projects down and to the left of F are within the available budget.

financial analysis, whereas a CBA in Not-for-profit organizations would include willingness-to-pay and willingness-to-accept measures to calculate the cost and benefits of non-monetary items. The NPV should be risk-adjusted to account for uncertainties in the calculation. (Phillips and Bana e Costa 2007).

MCDA maintains that the decision criterion should not only be to select a project that has a or the highest NPV, but the highest NPV *relative to investment costs*. A Cost-Benefit curve is used as decision metric, ranking projects according to benefit at cost. Unlike MATE, the solution generation is not systematic and no full tradespace is explored. MCDA has no explicit intent to enumerate and model *all possible* alternatives of a given decision. The emphasis is on a pragmatic “good enough” approach to make the best possible decision in a limited amount of time that decision-makers are prepared to spend on the issue.

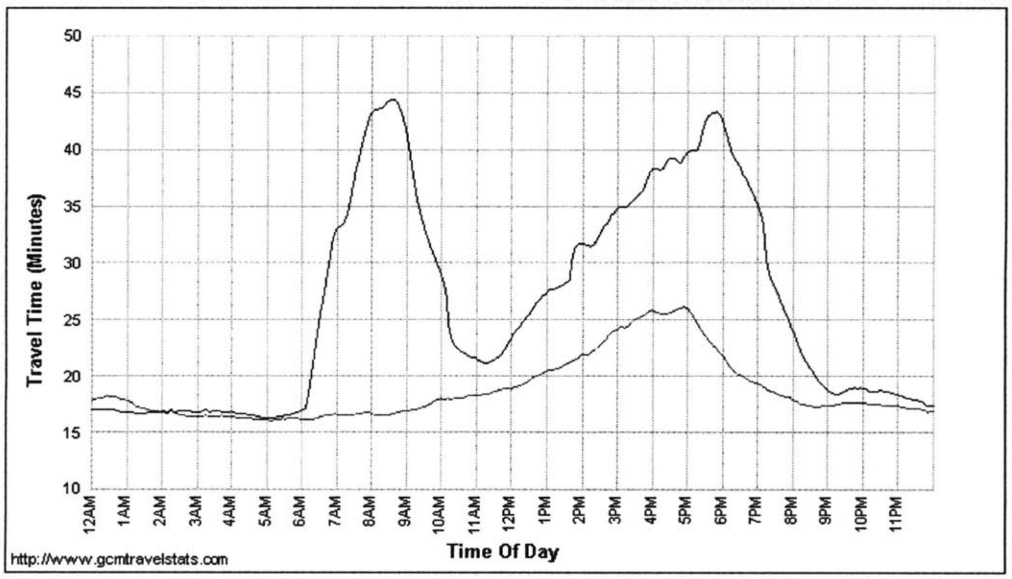
7.2 Appendix: Kennedy Expressway sample from 1/1/2004-1/12/2008

IL: EB KENNEDY from O'HARE to I-290/CIRCLE (16.33 miles) 10/01/2004 through 12/01/2008 Sunday, Saturday

Travel Time (minutes) Segment 1				
Line Color	Average	Min Average	Max Average	Avg Sample Days
Red	18.78	16.03 (5:05AM)	26.15 (4:50PM)	388.5

IL: EB KENNEDY from O'HARE to I-290/CIRCLE (16.33 miles) 10/01/2004 through 12/01/2008 Monday, Tuesday, Wednesday, Thursday, Friday

Travel Time (minutes) Segment 2				
Line Color	Average	Min Average	Max Average	Avg Sample Days
Blue	26.32	16.28 (4:55AM)	44.37 (8:30AM)	974.0



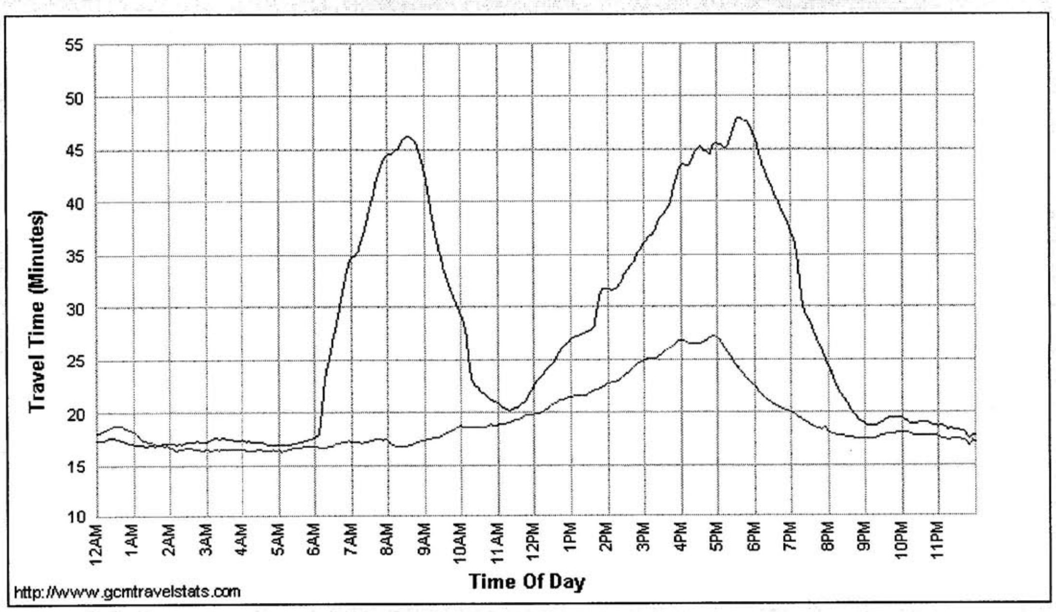
7.3 Appendix C: Sample from 1/1/2008-1/12/2008

IL: EB KENNEDY from O'HARE to I-290/CIRCLE (16.33 miles) 01/01/2007 through 12/01/2008 Sunday, Saturday

Travel Time (minutes) Segment 1				
Line Color	Average	Min Average	Max Average	Avg Sample Days
Red	19.26	16.25 (2:10AM)	27.18 (4:50PM)	190.0

IL: EB KENNEDY from O'HARE to I-290/CIRCLE (16.33 miles) 10/01/2007 through 12/01/2008 Monday, Tuesday, Wednesday, Thursday, Friday

Travel Time (minutes) Segment 2				
Line Color	Average	Min Average	Max Average	Avg Sample Days
Blue	27.38	16.80 (1:20AM)	48.02 (5:35PM)	290.9

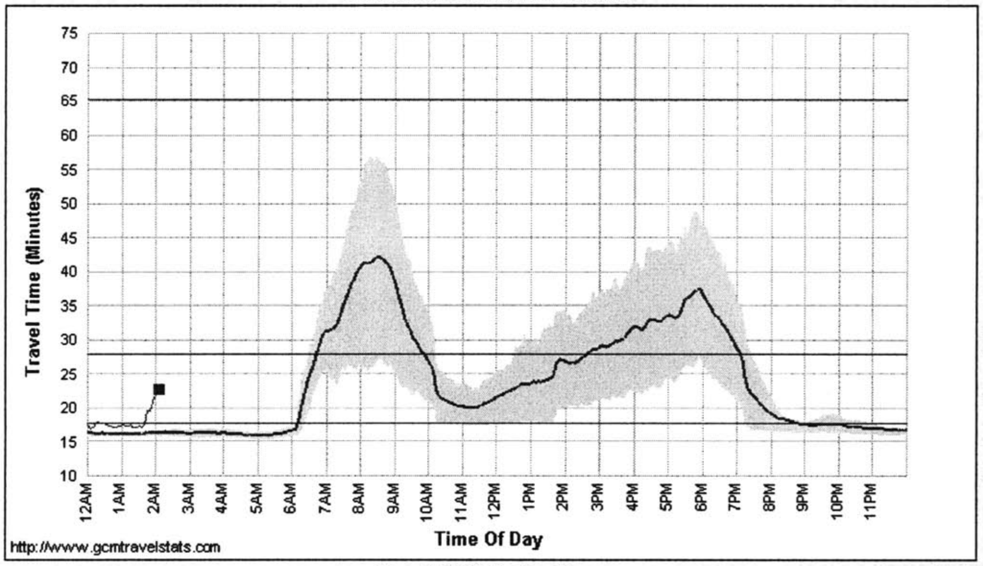


7.4 Appendix: Kennedy Expressway travel time variance

IL: EB KENNEDY from O'HARE to I-290/CIRCLE (16.33 miles) Monday

Travel Time (minutes) 2:05AM			
Current	Average	Difference	Sample Days
22.65	16.40	+6.25	199

Most Recent Data: 12/1/2008 2:05:00 AM



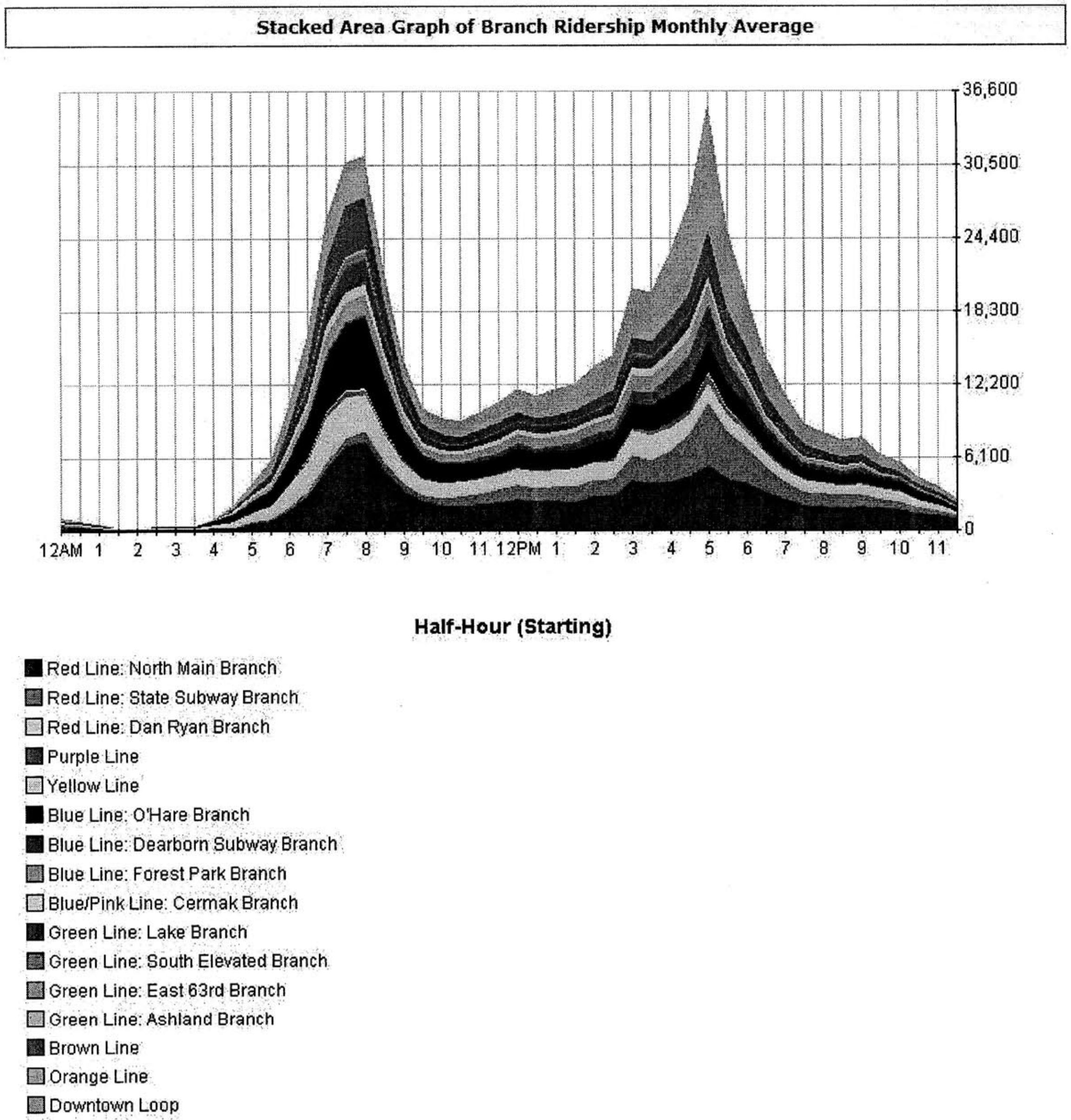
More Detail | Custom Query

Current Travel Time: The green line indicates the actual travel time for all samples collected on the date which data was most recently collected. The most recent travel time collected is shown on the chart as a green square. Gaps in the green line indicate no data was recorded for the given time.

Average Travel Time: The red line indicates the average travel time for all samples ever collected. Gaps in the red line indicate no data has ever been recorded for the given time.

Normal Range: The yellow fill area indicates the normal range, based on percentiles, of travel time values for the given time period. Current travel times above or below the average are common. Current travel times outside the yellow fill area are less common. Approximately 68% of all travel times will occur within the yellow fill area.

Speed Thresholds: The dark blue lines indicate speed thresholds. The bottom line indicates the travel time if moving at 55MPH (no traffic congestion). The middle line indicates the travel time if moving at 35MPH (medium traffic congestion). The top line indicates the travel time if moving at 15MPH (heavy traffic congestion).



2008 Monthly Ridership per Branch (Source: CTA). The Blue Line O'Hare Branch is one of the busiest lines.

7.5 Appendix: Emission parameters

HIGHWAY EMISSIONS FACTORS (g/mi)

Model Year 2003

Mode	Speed	CO	NO_X	PM_{10}	SO_X	VOC	% of vehicles on Kennedy Expressway at that speed
Auto	22	10.38	0.95	0.05	0.01	0.95	0.16
	25	9.75	0.90	0.04	0.01	0.88	0.10
	28	9.29	0.88	0.04	0.01	0.83	0.09
	33	8.64	0.84	0.04	0.00	0.77	0.11
	39	8.10	0.81	0.03	0.00	0.73	0.14
	49	7.68	0.81	0.03	0.00	0.70	0.12
	58	7.86	0.86	0.03	0.00	0.72	0.28

HIGHWAY EMISSIONS FACTORS (g/mi)

Model Year 2003

Mode	Speed	CO	NO_X	PM_{10}	SO_X	VOC
Bus	20	28.62	15.56	0.42	0.14	3.24
	41	13.96	12.93	0.22	0.13	1.36

PASSENGER TRAIN EMISSIONS FACTORS

(g/train-mile)

Mode	CO	NO_X	PM_{10}	SO_X	VOC
Passenger Train	45.67	583.58	62.02		19.73

Line	Average speed (mph)
Blue Line	20.4
BRT	40.8
Local bus	20.4

7.6 Appendix: Summary of Airport Express model

Table 7-1: *Expense and Utility for the three decision makers*

Attributes	DM	Metric			Weight	Abbreviation
Expense			**Min acc e=1**	**Max acc e=0**		
City's initial cost	City	$M	640	100	0.16	CIC
City's cost share	City	%	50%	10%	0.12	CCS
CTA initial cost	CTA	$M	100	0	0.2	CTAC
Operating costs	PO	$/day	10,000	0	0.1	OC
Concession payment	PO	$M	500	0	0.2	CP
Utility			**u=0**	**u=1**		
QOS	City	Scale [1 to 5]	2	5	0.28	QOS
Span of service	CTA	Hrs/day	24	18	0.1	MT
QOS_PO	PO	Scale [1 to 5]	0	5	0.2	QOS_PO
Freedom to make changes	PO	Scale [1 to 5]	1	5	0.15	FC
Competition Agreements	PO	Scale [1 to 5]	3	5	0.15	AB

Table 7-2: *Design variables*

DVs	Range	Measure	Abbreviation	Number
Concept	[1, 2, 3]	Route 2, BRT, BLS	Concept	1
Fare level	[10, 20]	$	Fare	2
Frequency	[5, 20]	headway in min	Freq	3
Travel time	[20, 30]	min	Time	4
Amenities	[1,2,3,4,5]	Qualitative Scale, 5 most amenities	Amenities	5
Span of service	[16, ...,24]	hr/day	Span	6
City cost share	[10, 50]	%	CityCostShare	7
Freedom to make changes	[1,2,3,4,5]	Qualitative Scale, 5 most freedom	Freedom	8
Competition agreements	[1,2,3,4,5]	Qualitative Scale, 5 most protection from competition	Competition	9
CTA payment	[0, 100]	$M	CTA	10

Table 7-3: *Intermediate Variable*

Intermediate Variables	Range	Measure	Abbreviation	Number
Total construction cost		$M	TCC	1

Table 7-4: *Design variables for City*

DVs	Range	Measure
Concept	[1, 2, 3]	Route 2, BRT, BLS
Fare level	[5, 20]	$
Frequency	[5, 20]	headway in min
Travel time	[20, 30]	min
Amenities	[1,2,3,4,5]	Scale
Span of service	[16, 24]	hr/day
Cost share City	[0.10, 0.50]	%

Table 7-5: *Design variables for the Private Operator*

Design variables	Range	Measure
Choice of concept	[1,2,3]	Route 2, BRT, BL Switch
Fare level	[10, 35]	$
Frequency	[5, 20]	headway in min
Travel time	[20, 30]	min
Amenities	[1,2,3,4,5]	Scale
Span of service	[16, 24]	hr/day
Freedom to make changes	[1, 5]	Scale
Competition agreement, ability to raise fares	[2, 5]	Scale

Table 7-6: *CTA Design variables and ranges*

DVs	Range	Measure
Up front investment requirement from CTA	[0, 100]	$M
Span of service	[16, 24]	hrs/day

7.6.1 Utility and expense function

Multi-attribute utility function (x_i denotes Attribute X^i, w_i denotes the normalized linear weighting factor for attribute X^i, γ characterizes shape of utility function)

$$U_{xi}=\sum_{xi} w_i * \frac{xi-\min(xi)}{(\max(xi)-\min(xi))^\wedge\gamma}$$

Multi-attribute expense function (x_i denotes Attribute X^i, w_i denotes the normalized linear weighting factor for attribute X^i, δ characterizes shape of expense function)

$$E_x=\sum_{xi} w_i * \frac{xi-\min(xi)}{(\max(xi)-\min(xi))^\wedge\delta}$$

7.6.2 Attribute calculations

```
Quality of Service
QOS=((Scale_of_Five-
(Frequency_minus_Frequency_min/Normalizing_constant_for_scale_of_five)+
2*(Scale_of_Five-
Fare_minus_Fare_min)/Normalizing_constant_for_scale_of_five))
+(Scale_of_Five-
(Time_minus_time_min)/Normalizing_constant_time)+Amenities/Scale_of_Five+Span
_minus_workday/(Normalizing_constant_span))/Normalizing_constant_QOS


Quality of Service for Private Operator
QOS_PO=((Scale_of_Five-
(Frequency_minus_Frequency_min/Normalizing_constant_for_scale_of_five)+2*
(Fare_minus_Fare_min/Normalizing_constant_for_scale_of_five))+(Scale_of_Five-
(Time_minus_time_min)/Normalizing_constant_time)+Amenities/Scale_of_Five+(Spa
n_minus_workday)/(Normalizing_constant_span))/Normalizing_constant_QOS

Total construction cost

Route                                                                      2:
TCC=Route_2_construction_cost+Train_vehicle_cost+Amenities*More_amenities_cco
st_Route2+(Low_travel_time-
Time)*Reduced_travel_time_minute_ccost_Route2+(Low_frequency-
Frequency)*More_frequency_ccost_Route2

BRT:
TCC=BRT_station_cost+BRT_vehicle_cost+Amenities*More_amenities_ccost_BRT+(
Low_travel_time-Time)*Reduced_travel_time_minute_ccost_BRT+(Low_frequency-
Frequency)*More_frequency_ccost_BRT

BLS:
TCC=BLS_cost_of_new_buses+Train_vehicle_cost+Amenities*More_amenities_ccost_B
LS+(Low_travel_time-
Time)*Reduced_travel_time_minute_ccost_BLS+(Low_frequency-
Frequency)*More_frequency_ccost_BLS


City Cost share
CCS=CityCostShare;

CityInitialCost
CIC= TCC*CCS;
```

Operating Cost
Route 2:

OC=Average_Fuel_cost_day_Route2+Average_personnel_operations_cost_day_Route2+Average_personnel_maintenance_cost_day_Route2+(Span-hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost_day_Route2+Amenities*More_amenities_cost_Route2 +(Expected_travel_time-Time)*Reduced_travel_time_minute_cost_Route2+(Low_frequency-Frequency)*Reduced_headway_minute_cost_Route2

BRT:

OC=Average_Fuel_cost_day_BRT+Average_personnel_operations_cost_day_BRT+Average_personnel_maintenance_cost_day_BRT+(Span-hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost_day_BRT/hours_per_workday+Amenities*More_amenities_cost_BRT +(Expected_travel_time-Time)*Reduced_travel_time_minute_cost_BRT+(Low_frequency-Frequency)*Reduced_headway_minute_cost_BRT

BLS:

OC=Average_Fuel_cost_day_BLS+Average_personnel_operations_cost_day_BLS+Average_personnel_maintenance_cost_day_BLS+(Span-hours_per_workday)*overtime_factor_per_hour*Average_personnel_operations_cost_day_BLS+Amenities*More_amenities_cost_BLS +(Expected_travel_time-Time)*Reduced_travel_time_minute_cost_BLS+(Low_frequency-Frequency)*Reduced_headway_minute_cost_BLS

Concession payment (how much money Private Operator is willing to pay to operate a given system)

Route 2:
CP=Concession_fix_Route2+Competition*Less_competition_willingness_to_pay_Route2+Freedom*More_freedom_willingness_to_pay_Route2 +More_freedom_and_less_competition_together_willing_to_pay_Rte2*Competition*Freedom+Amenities*More_amenities_willingness_to_pay_Route2

BRT:
CP=Concession_fix_BRT+Competition*Less_competition_willingness_to_pay_BRT+Freedom*More_freedom_willingness_to_pay_BRT +More_freedom_and_less_competition_together_willing_to_pay_BRT*Competition*Freedom+Amenities*More_amenities_willingness_to_pay_BRT;

BLS:
CP=Concession_fix_BLS+Competition*Less_competition_willingness_to_pay_BLS+Freedom*More_freedom_willingness_to_pay_BLS +More_freedom_and_less_competition_together_willing_to_pay_BLS*Competition*Freedom+Amenities*More_amenities_willingness_to_pay_BLS

Freedom to make changes
FC=Freedom

Competition agreements
AB=Competition

```
Maintenance time
MT=hours_per_day- Span

CTA Cost Contribution
CTAC=CTA

Constants
hours_per_workday = 16
hours_per_day= 24
overtime_factor_per_hour = 1+1/8; % WAG
Scale_of_Five= 5; %for dimensionless attributes
Normalizing_constant_for_scale_of_five= 3; % divide by 3 to convert to scale
from 1-5, use for frequency and fare
Normalizing_constant_time= 2;
Normalizing_constant_span= 8/5;
Normalizing_constant_QOS= 6; %5 factors, one doubled

Low_travel_time=30; % mins
Low_frequency=25; %headway
Expected_travel_time = 30; % mins WAG


(Sources of data points are outlined in Section 4.6)
Assumptions for City Capital Cost Calculation
Route_2_construction_cost=480; $M
Train_vehicle_cost=50.4; $M
BRT_station_cost=2.5; $M
BRT_vehicle_cost=5.6; $M
BLS_cost_of_new_buses=107; $M
Frequency_min= 5; % 5 minute headway
Frequency_max= 20; % 20 minute headway
Fare_min= 5; % $5 minute headway
Fare_max= 20; % $20 minute headway

(Sources of data points are outlined in Section 4.6)
Assumptions for Operating Costs
Average_Fuel_cost_day_Route2=2112; % $
Average_personnel_operations_cost_day_Route2= 1856; %$
Average_personnel_maintenance_cost_day_Route2= 5568; %$
Average_Fuel_cost_day_BRT=2870; % $
Average_personnel_operations_cost_day_BRT= 2784; %$
Average_personnel_maintenance_cost_day_BRT= 2784; %$
Average_Fuel_cost_day_BLS=2558; % $
Average_personnel_operations_cost_day_BLS= 1856; %$
Average_personnel_maintenance_cost_day_BLS= 5568; %$


Frequency_minus_Frequency_min= Frequency-Frequency_min; % ranges from 0 to 15
Fare_minus_Fare_min= Fare-Fare_min; % ranges from 0 to 15
Span_minus_workday= Span-16;
Time_minus_time_min= Time-20; %min

Construction cost WAGS
More_frequency_ccost_Route2= 5; % $M
More_frequency_ccost_BRT= 0.5; %$M
```

```
More_frequency_ccost_BLS= 5; %$M

More_amenities_ccost_Route2= 4; %$M
More_amenities_ccost_BRT= 6; %$M
More_amenities_ccost_BLS= 4; %$M

More_frequency_ccost_Route2= 5; %$M
More_frequency_ccost_BRT= 0.5; %$M
More_frequency_ccost_BLS= 5; %$M

Reduced_travel_time_minute_ccost_Route2= 2; %$M
Reduced_travel_time_minute_ccost_BRT= 3; %$M
Reduced_travel_time_minute_ccost_BLS= 2; %$M

Operating cost WAGS
Reduced_headway_minute_cost_Route2= 300; %$/day
Reduced_headway_minute_cost_BRT= 400; %$/day
Reduced_headway_minute_cost_BLS= 300; %$/day

Reduced_travel_time_minute_cost_Route2= 300; %$/day
Reduced_travel_time_minute_cost_BRT= 400; %$/day
Reduced_travel_time_minute_cost_BLS= 400; %$/day

More_amenities_cost_Route2= 500; %$/day
More_amenities_cost_BRT= 300; %$/day
More_amenities_cost_BLS= 500; %$/day

Concession payment willingness to pay WAGS
Concession_fix_Route2= 100; %$M
Concession_fix_BRT= 0; %$M
Concession_fix_BLS= 70; %$M

Less_competition_willingness_to_pay_Route2= 20; %$M
Less_competition_willingness_to_pay_BRT= 10; %$M
Less_competition_willingness_to_pay_BLS= 20; %$M

More_freedom_willingness_to_pay_Route2= 20; %$M
More_freedom_willingness_to_pay_BRT= 20; %$M
More_freedom_willingness_to_pay_BLS= 20; %$M

More_amenities_willingness_to_pay_Route2= 5; %$M
More_amenities_willingness_to_pay_BRT= 5; %$M
More_amenities_willingness_to_pay_BLS= 5; %$M

More_freedom_and_less_competition_together_willing_to_pay_Rte2= 10; %$M
More_freedom_and_less_competition_together_willing_to_pay_BRT= 10; %$M
More_freedom_and_less_competition_together_willing_to_pay_BLS= 10; %$M
```

7.7 Appendix: HSR Case study

7.7.1 *Description of attributes for HSR case study*

Total project cost (Portuguese side)	The total cost of the engineering, planning, infrastructure construction, construction of stations, border stop, and purchase of vehicles from Sines/Lisboa to the border stop
Cost-Portuguese Share	Share of project cost that Portugal has to bear. Cost shares of all stakeholders need to add up to 100%
Cost-EU share	Share of project cost that the EU will provide (contributes only to certain expenses, share for those expenses needs to be converted to EU share of total project cost on Portuguese side).
Cost –Spain Share (Border Connection)	Total share of cost for border connection (physical connection and station) that Spain incurs. The cost Portugal incurs is (100%- Spain share). Spain will not contribute to the construction of any other part of the HSR system in Portugal.
Private Investor Contribution	Money borrowed from a private source which has to be serviced with interest according to the market rate. This contribution bridges the shortfall between the funds Portugal and the EU can jointly provide.
Cost-Maintenance	Annual cost of track, other infrastructure and vehicle maintenance for the track portion from Sines/Lisbon to the border stop.
Cost-Operations	Annual cost of train operations from Sines/Lisbon to Madrid at a fixed frequency.
Portuguese cost share of operations	Cost share incurred by Portugal for operating the trans-border train line and the border stop, plus train transit charges owed to Spain, minus train transit payments received from Spain. Train transit charges are part of the allocation of cost between two countries for trans-border connections, for example for Spanish employees working on a train that crosses into Portugal and travels to Lisbon.
Spanish cost share of operations	Cost share incurred by Spain for operating the trans-border train line and the border stop, plus train transit charges owed to Portugal, minus train transit payments received from Portugal. The sum of the Portuguese and Spanish cost shares of operation needs to be 100%.
Net travel time Lisbon-Madrid	Physical travel time for the distance from Lisbon to Madrid, not accounting for delays due to unloading, border crossing, and stopping activity. The calculation of this attribute consists of the following components: $T_{Net}=T_{\text{Lisbon-Border}} + T_{\text{Border- Madrid}} = \text{Average Speed}_{\text{Lisbon-Border}} * \text{track length}_{\text{Lisbon-Border}} +$ $\text{Average Speed}_{\text{Border- Madrid}} * \text{track length}_{\text{Border- Madrid}}$ Intermediate variables (dependent upon): distance Lisbon-border port

	(border port location, network routing), distance border port-Madrid (border port location, network routing), average speed (network routing, number of stops, train technology).
# Stops on Portuguese side	Number of scheduled stops between Lisbon and Madrid for passenger boarding
Overall travel time (pax)	Overall travel time for passengers from the point of boarding in Lisbon until their arrival at in Madrid, excluding purposeful delays so as to keep a minimum distance from other freight or passenger trains. The calculation of this attribute consists of the following components: $T_{overall\_pax}$=average travel speed $_{Lisbon\text{-}border\ port}$* distance$_{Lisbon\text{-}border\ port}$+ $T_{delays\ from\ stops}$* # stops + average travel speed$_{border\ port\text{-}Madrid}$* distance$_{border\ port\text{-}Madrid}$ + average stopping time* # stops Intermediate variables (dependent upon): distance Lisbon-border port (border port location, network routing), distance border port-Madrid (border port location, network routing), average speed (network routing, number of stops, train technology, % of route traveled at maximum speed). Constants: distance Lisbon- border port, border port-Madrid, # of intermediate stops on Spanish side, average stopping time at intermediate stops.
Overall travel time (freight)	Overall travel time for freight from the point of unloading from cargo ships at the Port of Sines (excluding unloading time and purposeful delays to maintain minimum spacing to other freight or passenger trains) until their arrival at the train station in Madrid. The calculation of this attribute consists of the following components: $T_{overall\_freight}$= $T_{Sines\text{-}Evora}$+$T_{reload\ in\ Evora}$ + $T_{Evora\text{-}border\ port}$+ $T_{border\ port\text{-}\ Madrid}$ + $T_{delays\ from\ stops}$* # stops $T_{overall\ freight}$= average travel speed $_{Sines\text{-}Evora}$* distance$_{Sines\text{-}Evora}$+ $T_{reload\ in\ Evora}$ + average travel speed$_{Evora\text{-}Madrid}$* distance$_{Evora\text{-}Madrid}$ + average stopping time* # stops Intermediate variables (dependent upon): distance Evora-border port (border port location, network routing), distance border port-Madrid (border port location, network routing), average speed (network routing, number of stops, train technology), $T_{reload\ in\ Evora}$ (penalty for loading from conventional rail onto HSR if HSR link Sines-Evora does not exist). Constants: distance Sines- Evora, average stopping time at intermediate stops, number of intermediate stops on Spanish side.

Quality of coordination at border connection	(Scale of 1-5) Quality of coordination of people and freight movement passing through the border stop. 1 denoting the least amount of coordination (e.g. uncooperative attitude of Portuguese and Spanish staff, need for reloading/unloading of freight, moving to different trains for passengers); 5 denoting a seamless integration of all processes (friendly and cooperative atmosphere between Portuguese and Spanish employees, smooth passage).
Max capacity (pax)	Maximum number of passenger trains that complete the trip Lisbon-Madrid-Lisbon per day. The following formula can be employed to calculate maximum capacity for homogeneous traffic (equal speed and spacing requirements). For mixed freight and traffic operations with differences in spacing, delays at stops and average travel time, capacity calculation needs to be based on a specific time schedule (Operations Research problem). If a slower travel time is acceptable, capacity may be increased if (slower) freight trains are a limiting factor on the joint tracks between Evora and Madrid. Formula for homogenous traffic: Max capacity= Cycle time/ minimum headways= $(2^*T_{\text{overall pax}})$ / minimum headway Intermediate variable: minimum headways (load, speed, track conditions)
Max throughput (freight)	Maximum number of cargo wagons that complete the trip from Sines to Madrid per day. The formula for homogeneous traffic and considerations from the previous attribute apply equally. Max Throughput= Cycle time/ minimum headways= $(2^*T_{\text{overall freight}})$ / minimum headway Intermediate variable: minimum headways (load, speed, track conditions)
Ease of Transfer to HSR in Evora	Binary variable. A penalty for changing loads from conventional rail to HSR in Evora is imposed if no HSR link between Evora and Sines should be built.
Risk (for private investor)	The risk to lose money for the private investor. The private investor lends money, which has to be serviced by interest and ultimately paid back in full. Depending on the risk, the private investor will ask for different rates of interest. The required interest payments drive total project cost.
Security	Avoidance of danger to life and health of travelers and Portuguese citizens from the HSR line. Dangers are caused by for example collisions, derailment, or being the target of terrorist attacks.
Prestige	This hard-to-measure attribute is derived from an improved impression of

	Portugal both within the country itself and internationally. An improved impression can stem for example from admiration for enhanced Portuguese transportation capabilities, technological advancement and willingness to invest in their country's economy and in green technologies.

7.7.2 *Epoch Variables for HSR case study*

Demand level	(tons of cargo/year) Number of tons of cargo annually that customers want to ship from Sines to Madrid or Madrid to Sines.
Demand level	(pax/year) Number of passengers who want to travel all or any part of the route Lisbon- Madrid or Madrid-Lisbon.
Mode share (cargo)	Percentage of demand for cargo transportation that is being shipped via HSR. Mode share depends on the relative attractiveness of HSR to other modes, based on factors such as reliability, price, speed, and ease of connection to other modes.
Mode share (pax)	Percentage of demand for passenger transportation on HSR between Madrid and Lisbon. Mode share depends on the relative attractiveness of HSR to other modes, based on factors such as reliability, price, frequency, speed, environmental friendliness, accessibility and convenience.
Economic situation of Portuguese major trading partners	1 is the worst, 5 is the best overall indicator for the economic state of the major trading partners France, Spain, Germany and Brazil. A level of 1 denotes a global economic recession, shortage of capital, and situation in which public investments are in fierce competition with each other. In level 5 the economy is booming and public money for investments is available. Depending on the economic situation of Portugal's major trading partner in the future, subsidies by Portugal and the EU may be put on hold and delay the project.
Portuguese Economy	(Scale 1-5) 1 is the worst, 5 is the best economic state of the local Portuguese economy. Level 1 denotes economic recession, shortage of capital, public investments are in fierce competition to each other. In level 5 the economy is booming and public money for investments is available.
Economic situation of Spain	(Scale 1-5) 1 is the worst, 5 is the best economic state of the Spanish economy. Level 1 denotes economic recession, shortage of capital, public investments are in fierce competition to each other. In level 5 the economy is booming and public money for investments is available.

Threat level	(Scale 1-5) The threat level denotes how much the country of Portugal feels threatened by outside actors. An increased threat level may for example arise from concerns for national safety and attacks, or from fear of a higher influx of illegal immigrants into the country.

7.8 Appendix: Interesting tradespaces by design variable

```
Max_OC= 25000; %$
Max_CP= 300; % $
Delta_po= 0.5
TCC-CIC-CTAC-CP)<=0
Delta_city= 0.5
Delta_cta= 0.5
num_runs=10000
```

Table 7-7: *"Cheat sheet" on Design Variables*

DVs	**Range**	**Measure**	**Abbreviation**	**Number**
Concept	[1, 2, 3]	Route 2, BRT, BLS	Concept	1
Fare level	[10, 20]	$	Fare	2
Frequency	[5, 20]	headway in min	Freq	3
Travel time	[20, 30]	min	Time	4
Amenities	[1,2,3,4,5]	Qualitative Scale, 5 most amenities	Amenities	5
Span of service	[16, ...,24]	hr/day	Span	6
City cost share	[10, 50]	%	CityCostShare	7
Freedom to make changes	[1,2,3,4,5]	Qualitative Scale, 5 most freedom	Freedom	8
Competition agreements	[1,2,3,4,5]	Qualitative Scale, 5 most protection from competition	Competition	9
CTA payment	[0, 100]	$M	CTA	10

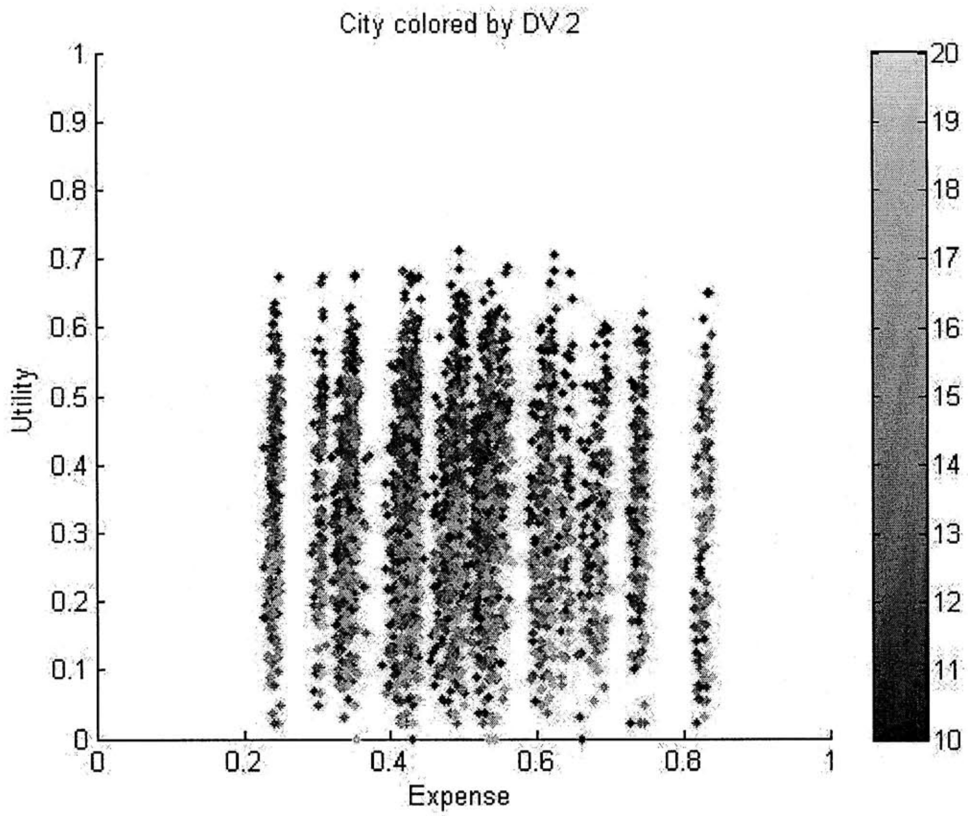


Figure 7-3: *City colored by fare (DV 2, in $)*

Pattern: Lower fares increase utility.

Explanation: Consequence of QOS model, which is increased by lower fares. The reasoning is that the City is interested in maximizing ridership so as to maximize the number of people and/or times these people benefit from the airport Express.

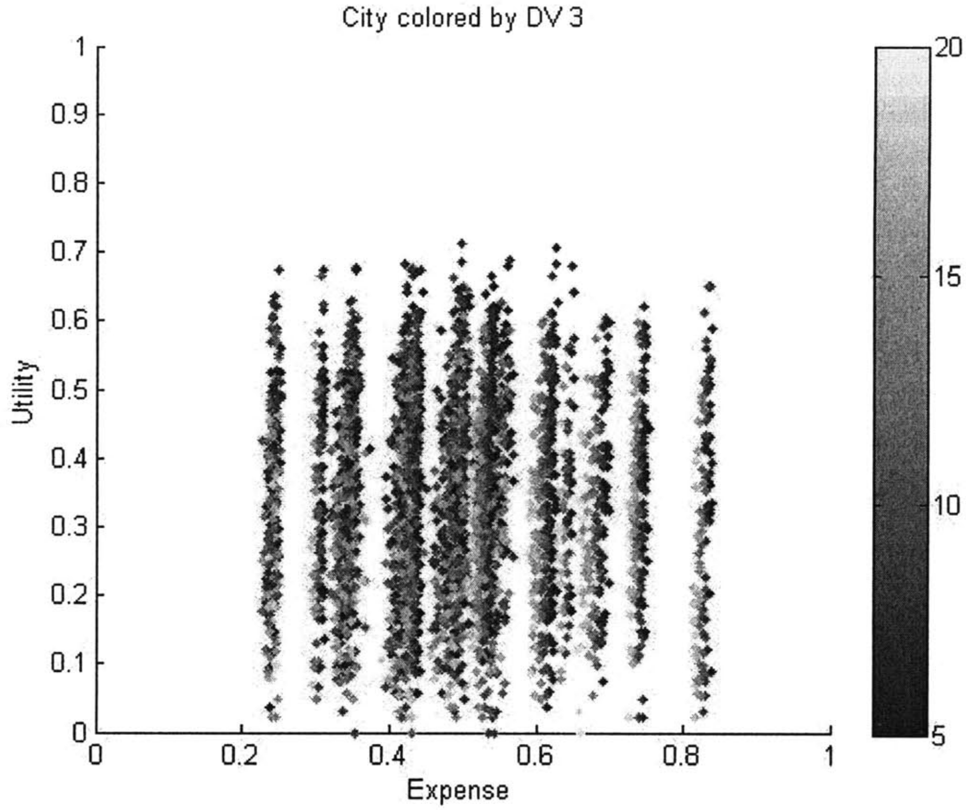


Figure 7-4: *City colored by frequency (DV 3, in minutes between trains)*

Pattern: Within a spike higher frequency increases expense very slightly for the more expensive designs, or does not show a clear pattern for cheaper designs. The designs with the highest utility values have low headways between trains (mostly 5 minute spacing, few 10 minute spacing).

Explanation: City benefits from a higher frequency, which translates to a better Quality of Service. Higher frequency has a small impact on initial costs, since more vehicles need to be purchased, and a high impact on operating costs. The City only contributes to initial costs, meaning that higher frequency is a perceived "cheap" way to increase utility.

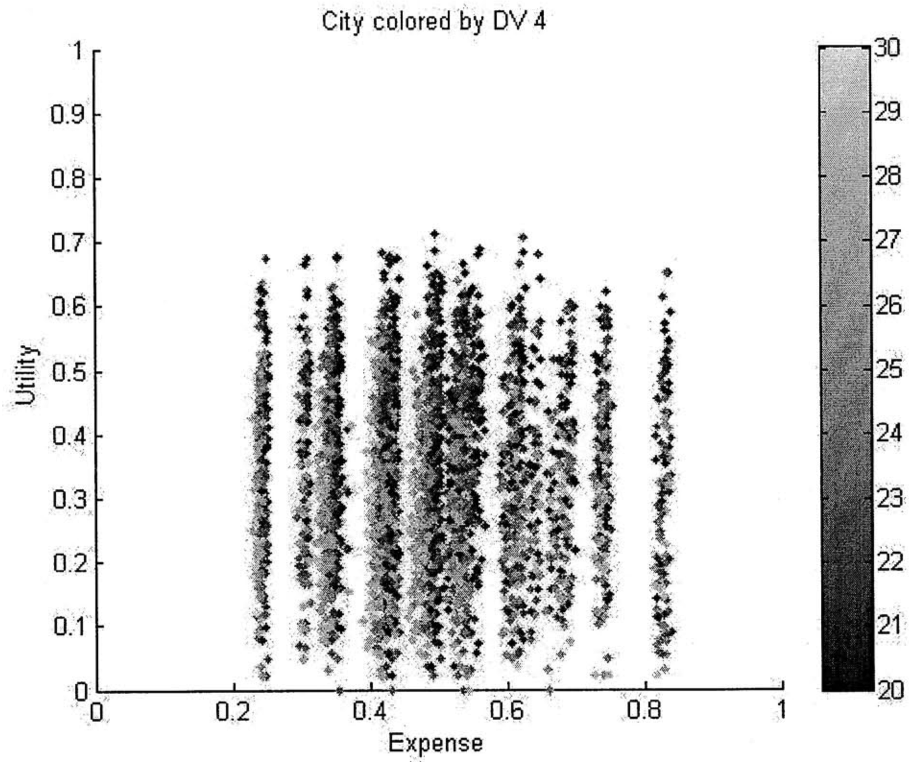


Figure 7-5: *City colored by travel time (DV 4, in min)*

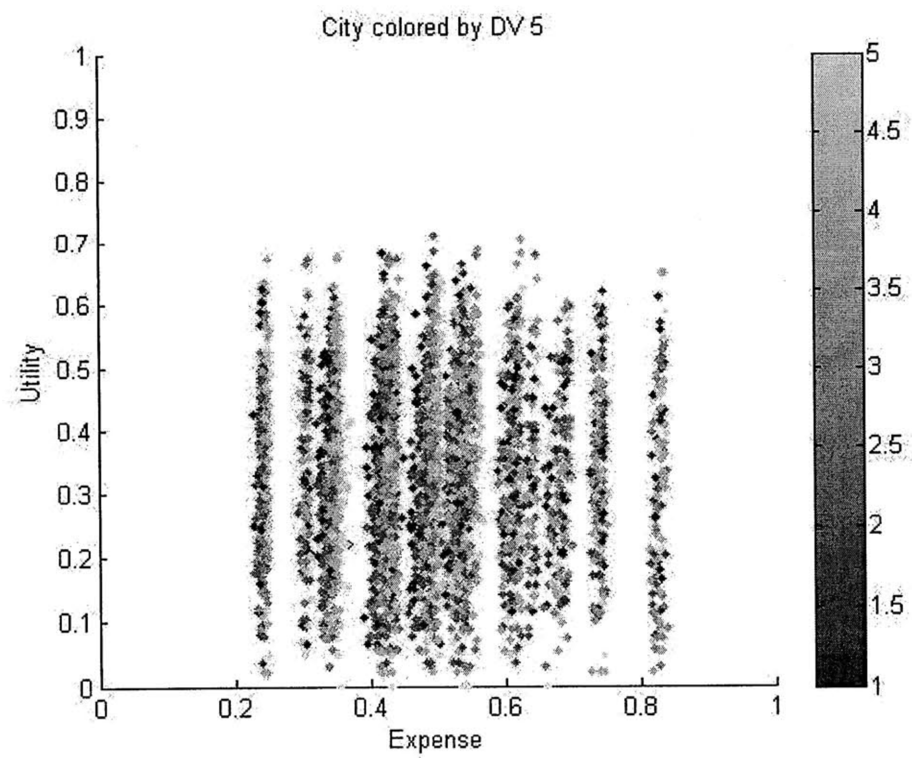


Figure 7-6: *City colored by amenities (DV 5, in points on 5-point scale)*

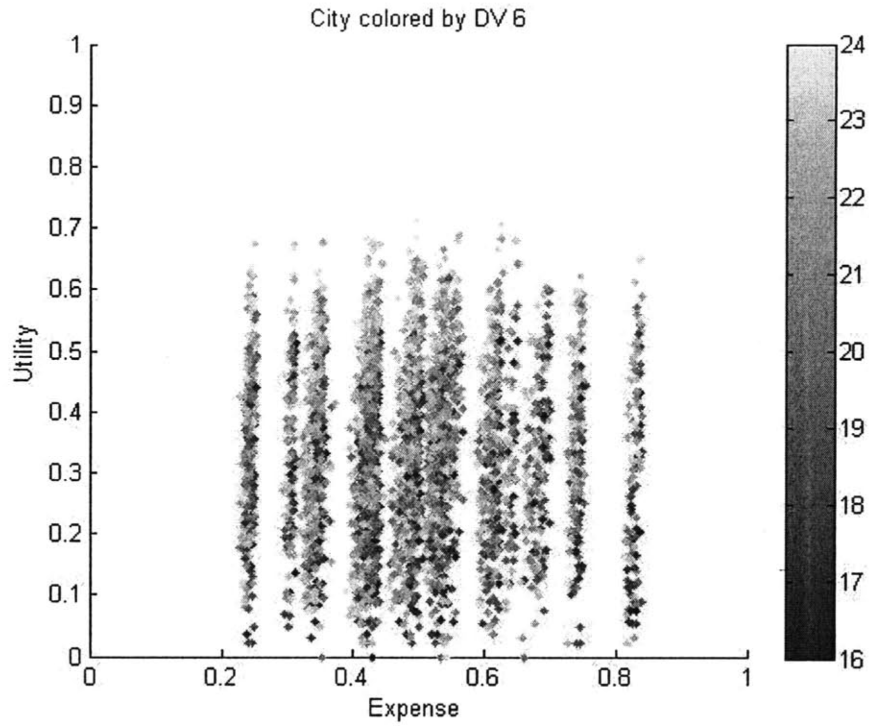


Figure 7-7: *City colored by span of service (DV 6, in hours per day)*

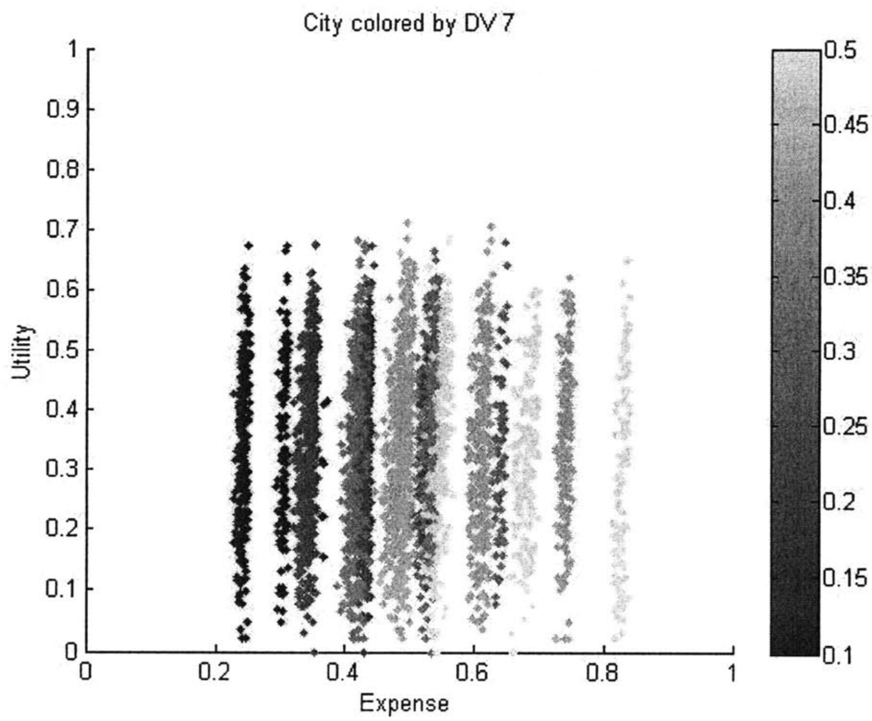


Figure 7-8: *City colored by City Cost Share (DV 7, %)*

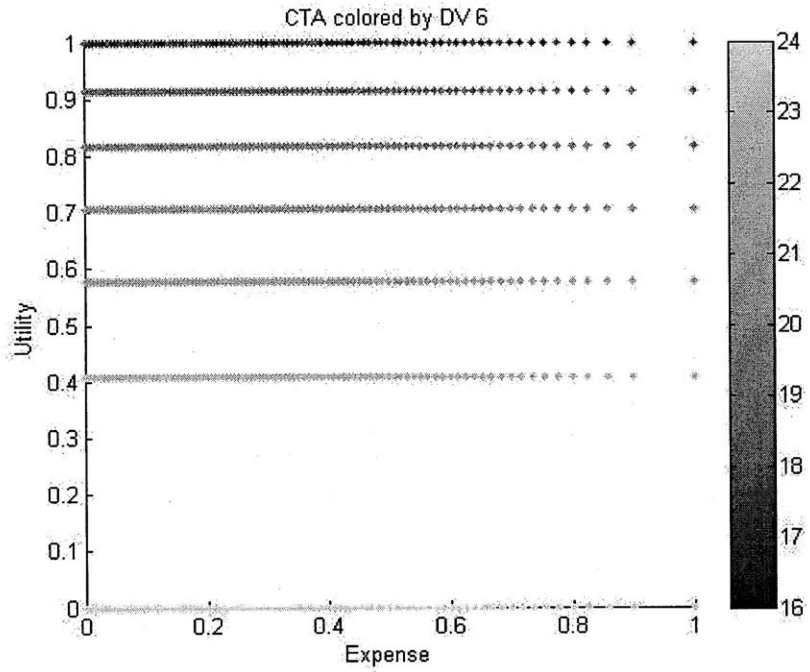


Figure 7-9: *CTA colored by span of service (DV 6, in hours per day)*

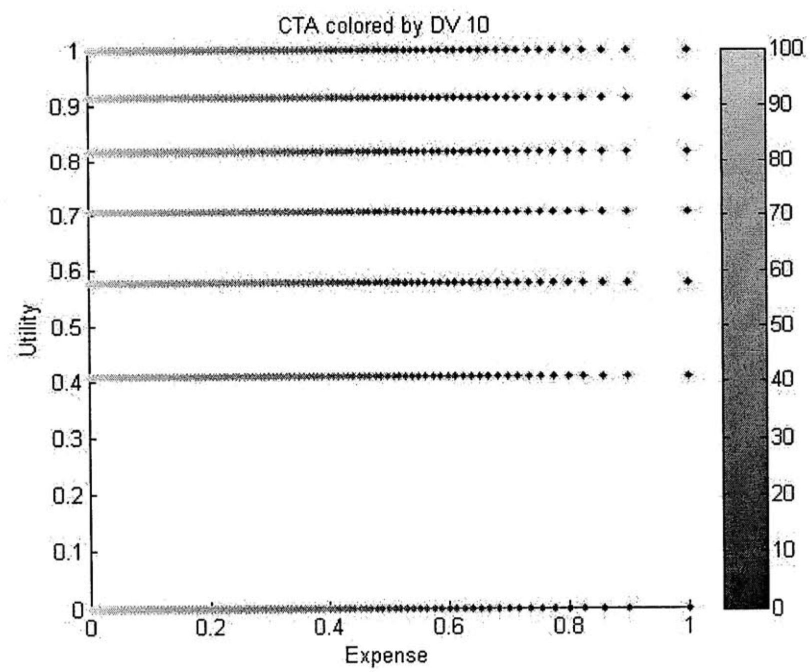


Figure 7-10: *CTA colored by CTA contribution to initial cost (DV 10, in $M)*

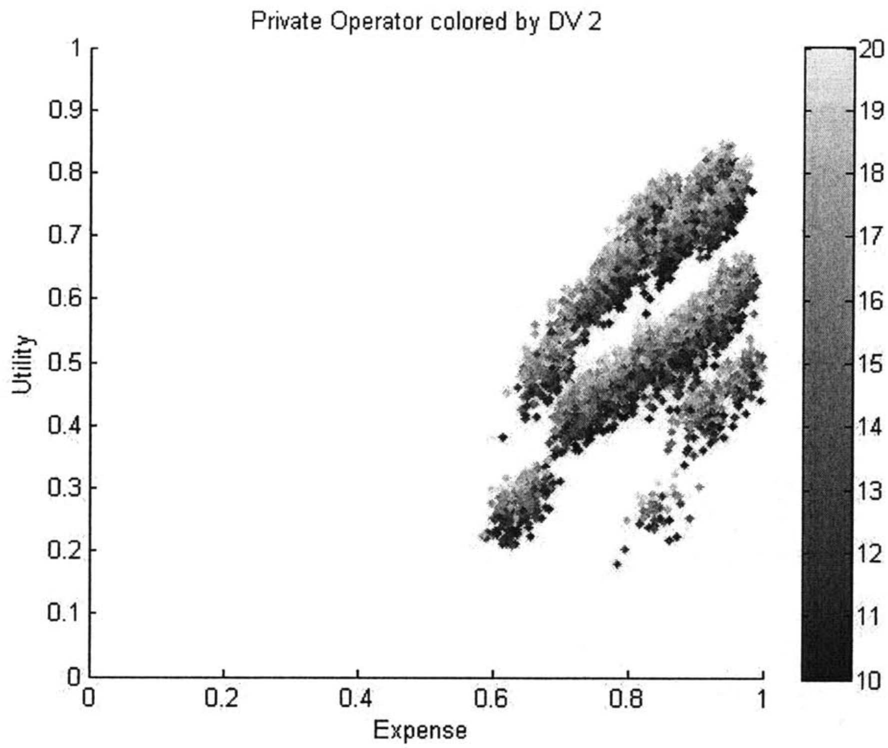


Figure 7-11: *Private Operator colored by Fare (DV 2, in $)*

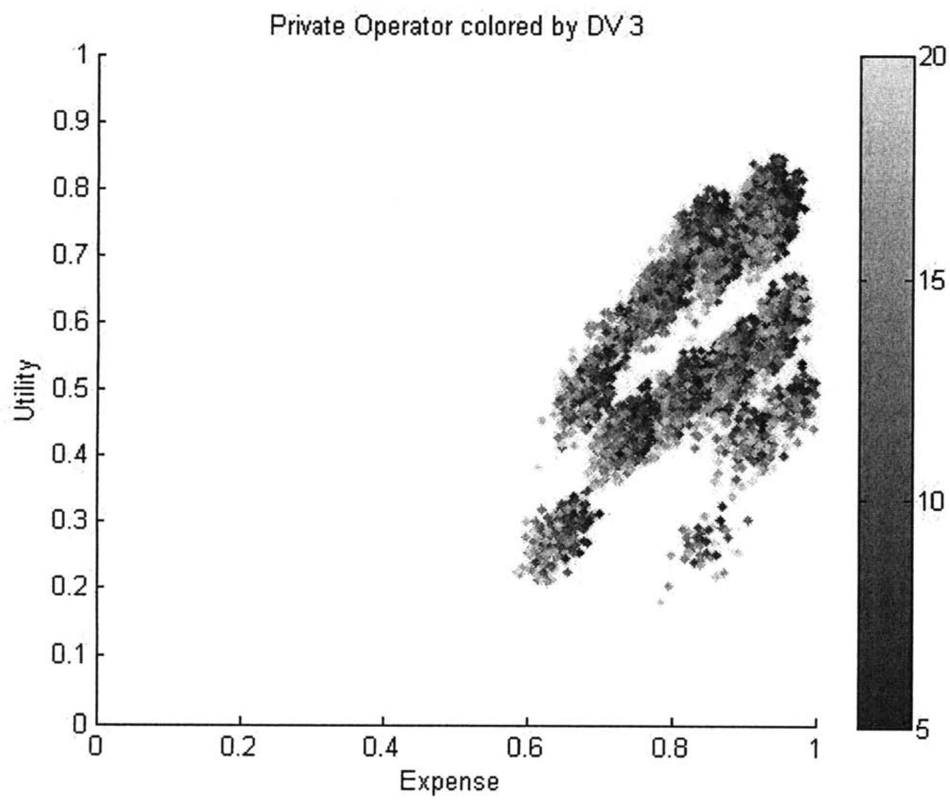


Figure 7-12: *Private Operator colored by frequency (DV 3, in headway in min)*

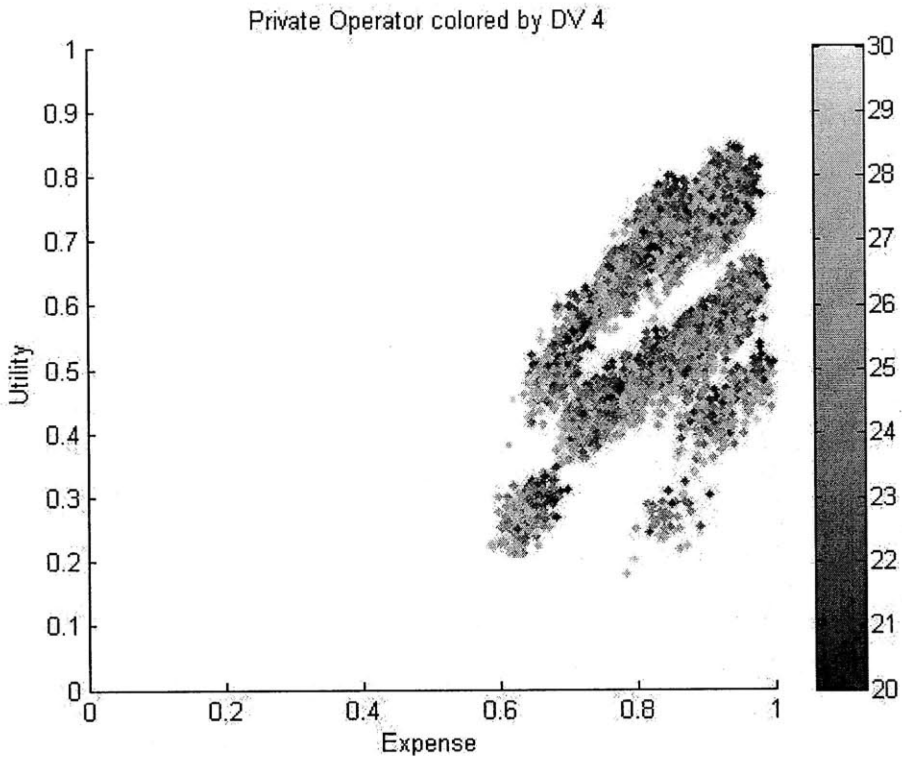


Figure 7-13: *Private Operator colored by travel time (DV 4, in min)*

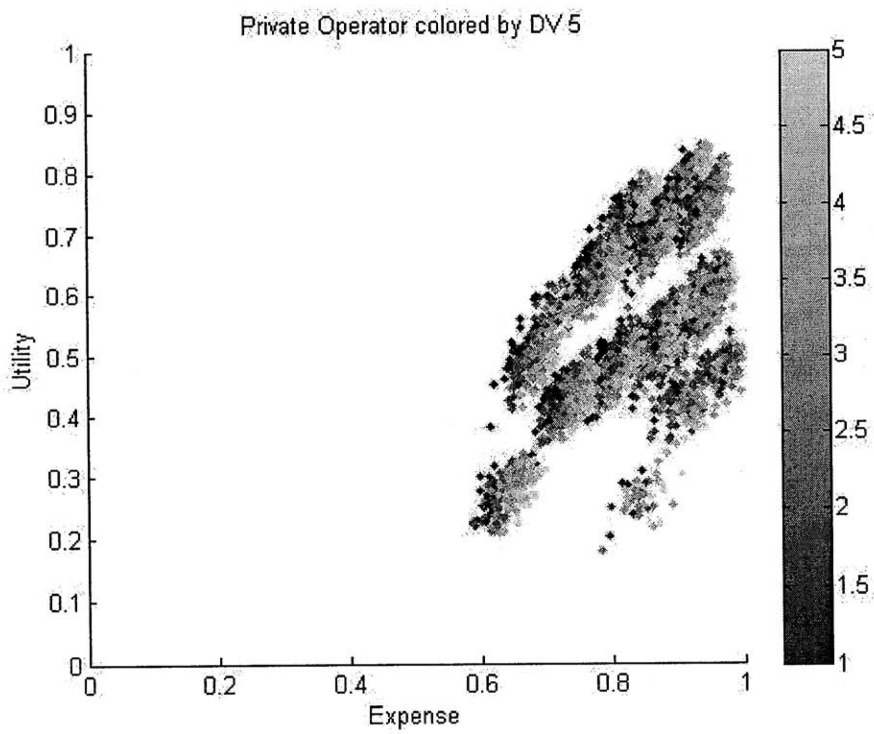


Figure 7-14: *Private Operator colored by amenities (DV 5, DV 5, in points on 5-point scale)*

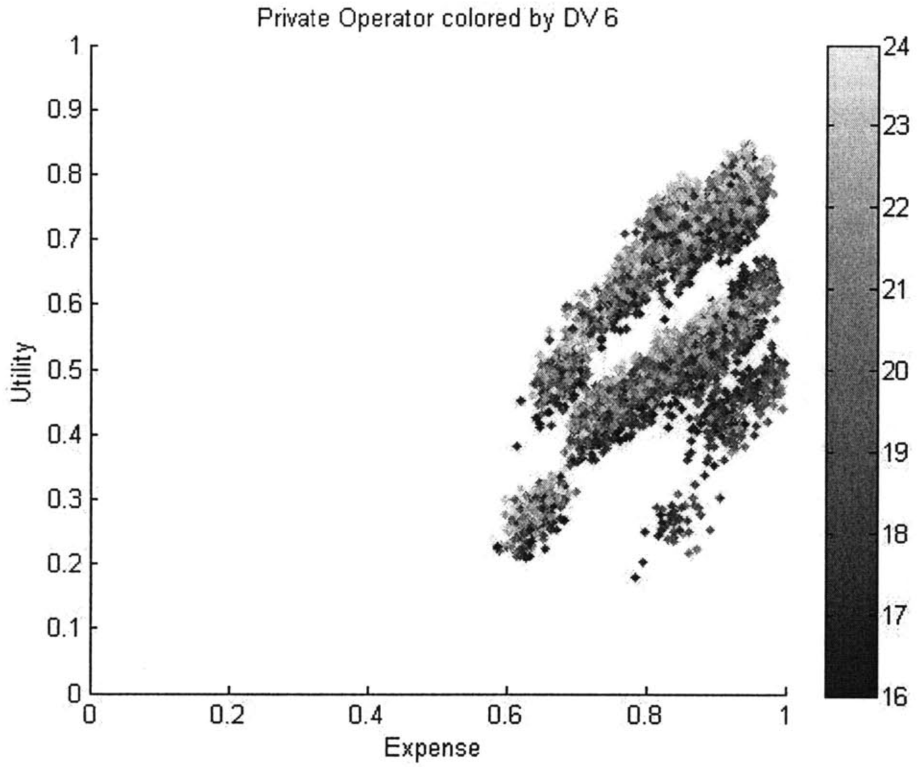


Figure 7-15: *Private Operator colored by Span of Service (DV 6, in hours per day)*

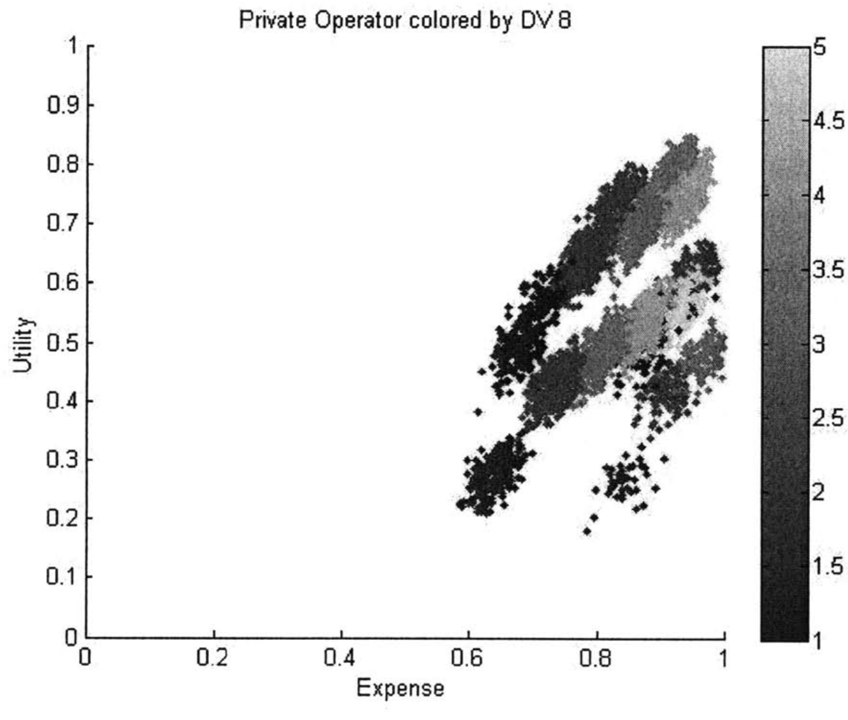


Figure 7-16: *Private Operator colored by Competition Agreements (DV 8, in points on a 5-point scale)*

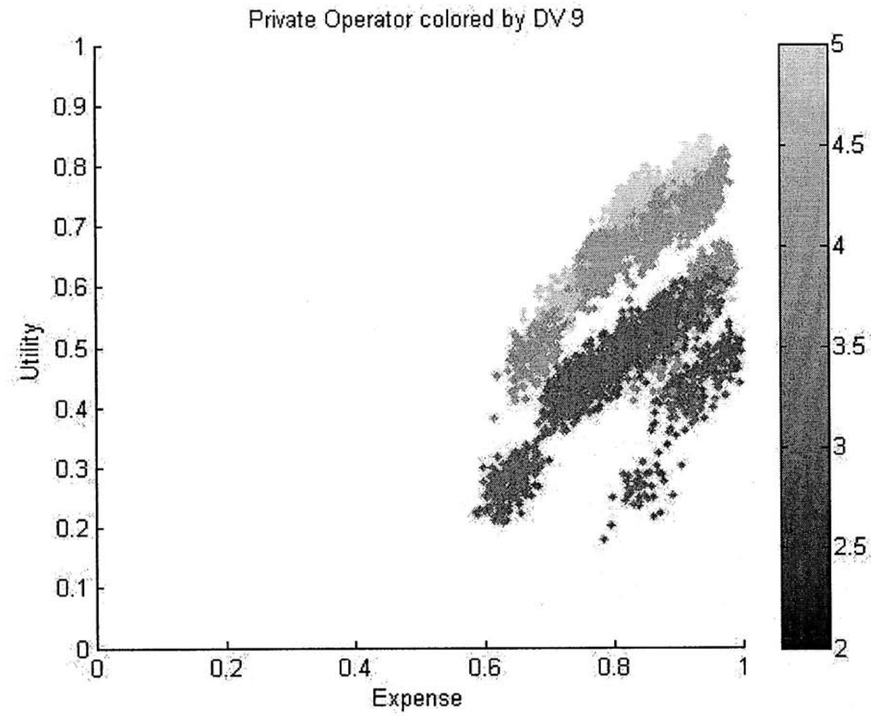


Figure 7-17: *Private Operator colored by Concessionaire Freedom to make changes (DV 9, in points on a 5-point scale)*

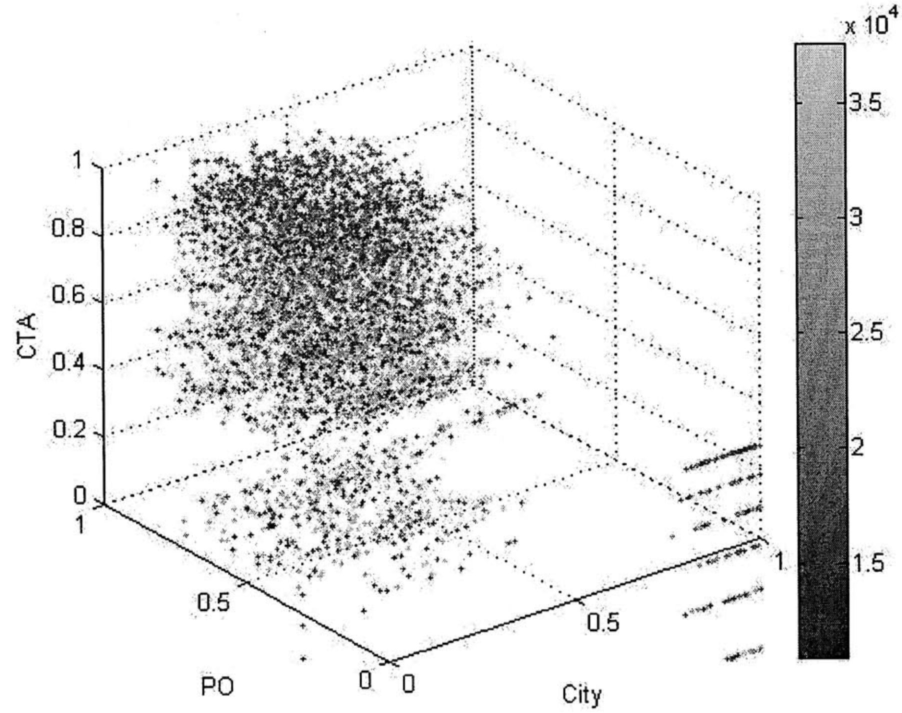


Figure 7-18: *Utility for City, CTA, PO, colored by Operating Cost (in \$/day)*

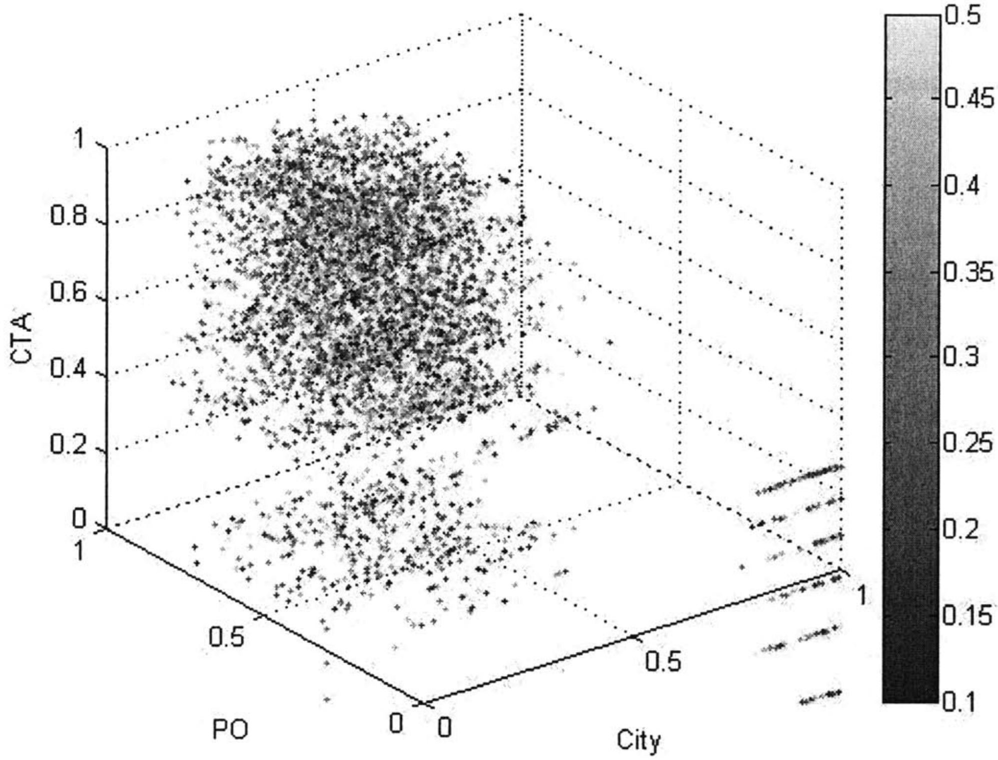


Figure 7-19: *Utility for City, CTA, PO, colored by Total Construction Cost (in B$)*

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